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A PILOT OPINION STUDY OF LATERAL CONTROL REQUIREMENTS

FOR FIGHTER-TYPE AIRCRAFT

By Brent Y. Creer, John D. Stewart, Robert B. Merrick,
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Ames Research Center
Moffett Field, Calif.

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SUMMARY

As part of a continuing NASA program of research on airplane handling qualities, a pilot opinion investigation has been made on the lateral control requirements of fighter aircraft flying in their combat speed range. The investigation was carried out using a stationary flight simulator and a moving flight simulator, and the flight simulator results were supplemented by research tests in actual flight.

The flight simulator study was based on the presumption that the pilot rates the roll control of an airplane primarily on a single-degree-of-freedom basis; that is, control of angle of roll about the aircraft body axis being of first importance. From the assumption of a single degree of freedom system it follows that there are two fundamental parameters which govern the airplane roll response, namely the roll damping expressed as a time constant and roll control power in terms of roll acceleration. The simulator study resulted in a criterion in terms of these two parameters which defines satisfactory, unsatisfactory, and unacceptable roll performance from a pilot opinion standpoint. The moving simulator results were substantiated by the in-flight investigation.

The derived criterion was compared with the roll performance criterion based upon wing tip helix angle and also with other roll performance concepts which currently influence the roll performance design of military fighter aircraft flying in their combat speed range.

INTRODUCTION

The requirements for satisfactory lateral control of fighter aircraft have been the object of numerous research projects. Notable contributions to the formulation of past roll requirements have been reported in references 1 through 3. Present research in this area seems to be focused on

two main objectives: (1) the determination of the roll performance required by an interceptor in order to successfully complete a specified combat mission; and (2) the determination of those parameters that primarily influence pilot opinion of aircraft lateral controllability.

The second of the above two listed problems is presently of real concern in that the roll response of some of the current fighter aircraft meet existing satisfactory requirements and yet the lateral controllability from a pilot opinion standpoint is unsatisfactory to the extent that the aircraft's combat usefulness is compromised. Hence, the specific objective of the present investigation was to determine the fundamental parameters which affect the pilot opinion of the rolling performance of fighter-type aircraft flying in their combat speed range. This investigation, which was carried out in the Flight Research Branch and Dynamics Analysis Branch of the Ames Research Center, made use of a stationary flight simulator and a moving flight simulator. The moving flight simulator involved only the roll degree of freedom. The simulator results were supplemented by research tests in actual flight.

NOTATION

b	wing span, ft
C_l	rolling-moment coefficient, $\frac{\text{rolling moment}}{\bar{q}Sb}$
$C_{l_{\delta_a}}$	$\frac{\partial C_l}{\partial \delta_a}$, per radian
C_{l_p}	$\frac{\partial C_l}{\partial (pb/2V)}$, per radian
h_p	pressure altitude, ft
I_X	moment of inertia of airplane about X axis, slug-ft^2
L_{δ_a}	$\frac{\bar{q}Sb}{I_X} C_{l_{\delta_a}}$, per sec^2
L_p	$\frac{\bar{q}Sb^2}{2VI_X} C_{l_p}$, per sec
p	rolling velocity, radians/sec

p_{ss}	steady-state rolling velocity, radians/sec
$\bar{q}$	dynamic pressure, lb/sq ft
S	wing area, sq ft
s	Laplace operator
t	time, sec
V	true airspeed, ft/sec
Φ	phase angle, deg
φ	bank angle, radians
δ_a	aileron deflection, radians
ρ	mass density of air, slugs/cu ft
τ	$-\frac{1}{L_p}$, roll time constant, sec
$(\dot{\ })$	derivative with respect to time

DESCRIPTION OF APPARATUS

As was noted in the Introduction, the present investigation made use of a stationary flight simulator and a moving flight simulator (involving roll degree of freedom only), and included flight tests with a number of different aircraft. The flight simulators consisted of an electronic analog computer for solving the airplane equations of motion and a fixed or moving cockpit for including the pilot in the control loop. For the simulator "flights," bank angle was the only quantity presented to the pilot and was displayed on an oscilloscope in the same fashion as it appears on a normal gyro horizon indicator. A block diagram showing the general flow of information for these flight simulators is presented as figure 1. A detailed description of the simulator setups and of the airplanes and flight instrumentation used in the investigation is given below.

Stationary Simulator

The fixed cockpit was modified from an F-86D airplane flight simulator with the result that the cockpit interior and controls closely resembled those of an actual airplane. A picture of the cockpit interior and the

pilot's display is presented as figure 2. (The line, on the oscilloscope, representing the horizon was obliterated in the picture taking process.) The maximum lateral stick deflection measured at the top of the stick was ±5 inches. The stick-to-aileron deflection was linear, and the stick force gradient was constant at 2 pounds per inch, which resulted in a maximum stick force of 10 pounds. It should be noted that the maximum stick deflection and maximum stick force values were typical of current fighter aircraft. The break-out force and friction forces were small and no viscous damping was present in the system. An opaque cockpit canopy was used during the testing period in order to isolate the test pilot from outside distractions.

Moving Simulator

The moving base simulator used in this investigation was capable of impressing both pitching and rolling motions on its occupant; however, the pitch degree of freedom was not utilized in this study. Hence the following discussion will be limited to a description of the cockpit, a cursory explanation of the electromechanical drive system, and a presentation of the response characteristics for the roll degree of freedom only. Figure 3(a) is an external picture of the moving simulator and figure 3(b) shows the instrument panel and internal layout of the cockpit. The revolution counter indicated the number of complete revolutions of the cockpit from a zero revolution position. The stick force and deflection characteristics of the moving simulator were similar to those of the stationary simulator.

The electromechanical roll drive servo system and its tie in with the analog computer is presented in block diagram form in figure 4. As indicated in this figure, the pilot's stick motion, which was converted into an appropriate voltage, was the input to the analog computer. The outputs from the computer were the desired bank angle, or computed bank angle, and its first and second derivatives. These derivatives of the desired bank angle were added to the command signal as a means of improving system response. This command signal was amplified and modified by several stages of electronic equipment. The first stage consists of a preamplifier that, in addition to amplifying, compares the command signal with the cockpit position to obtain an error signal. This error signal is then summed with the amplidyne voltage, generator current, and motor speed signals in the main power amplifiers. These latter signals were added to further increase system response and improve system stability. The amplidyne provides further amplification as it excites the fields of the two series-connected d-c generators. The generators, in turn, furnish the power for the 10-horsepower armature-controlled motor that drives the cockpit through a commercial speed reducer with a gear ratio of 15:1. The purpose of the nonlinear preamplifier gain, indicated in figure 4, is to prevent the system from becoming unstable for large error signals.

Figure 5 presents the frequency response of the system in terms of the amplitude ratio and phase angle between the cockpit motion, φ_O, and the desired bank angle, φ (see fig. 4). The magnitude of the input was such that the driven cockpit amplitude was approximately ±20° at the lower driving frequencies. The subject response curves were for gain values, K_2 and K_3 of figure 4, which were most frequently used in this investigation. It can be seen from figure 5 that an amplitude ratio of near 1 was maintained to a frequency of 10 radians per second, and the phase lag at this point was approximately 40°. From a consideration of the transient response to pilot-type aileron inputs, it was found that the measured cockpit motion closely duplicated the desired or computed value except in that region wherein high roll rates and high roll accelerations were commanded. A sample transient response to a series of ramp aileron inputs, which illustrates this point, is shown in figure 6. It can be seen that the measured roll rates and displacements lagged somewhat behind the computed values. The consequence of this will be discussed later in this report.

Airplanes and Flight Instrumentation

The airplanes used in the investigation included a propeller-driven fighter of World War II vintage, straight-wing jet-powered trainers, current operational interceptors of both the swept-wing and delta-wing type, and a variable-stability airplane. Two-view drawings of the airplanes tested with their pertinent geometric characteristics are shown in figure 7. Flight instrumentation was put only in those aircraft for which certain aerodynamic characteristics were not accurately known. This instrumentation consisted of a roll rate gyro, an oscillograph, and an aileron or lateral stick position recorder.

DESCRIPTION OF METHOD AND TEST

Inasmuch as the objective of this study was the determination of the basic parameters which influence pilot opinion of the airplane lateral response, the initial approach used was to consider only the single-degree-of-freedom rolling motion. The point of view was taken that the influence of the other modes of motion on the airplane roll response, such as either aerodynamic or inertia coupling, and the resulting effect on pilot opinion of the lateral controllability are of secondary importance in a well designed airplane. If, however, a high degree of coupling exists, it is usually a result of deficiencies in the dynamics of the other modes of motion and must be corrected before the roll performance of the airplane can rightfully be considered. The results of this study are offered as justification of this simplified approach.

The single-degree-of-freedom roll equation for an airplane may be written, in Laplace transform notation, as follows:

$$p(s) = \frac{\tau L_{\delta_a}\delta_a(s)}{\tau s+1}$$

It can be shown, reference 4, that the response with time is determined completely by the two quantities $L_{\delta_a}\delta_a$ and τ where τ is a measure of the roll damping and $L_{\delta_a}\delta_a$ is a measure of the aileron control power in terms of roll acceleration. For a given aileron input the steady-state roll velocity is given by the equation, $p_{ss} = \tau L_{\delta_a}\delta_a$. It is reasoned that in the presence of a reasonable stick-force gradient and control system dynamics, pilot opinion of the lateral controllability would correlate with τ and $L_{\delta_a}\delta_{a,max}$ where $L_{\delta_a}\delta_{a,max}$ is the maximum control power available. The purpose of the project was to investigate this premise. Figure 8 shows the variation of p_{ss} with τ and $L_{\delta_a}\delta_{a,max}$ and the extreme range of variables covered in the flight simulator investigation. More specifically, the evaluation was conducted mainly for constant values of $\tau = 0.1$, 0.2, 0.4, 1, 2, and 4 seconds, with the maximum variation in $L_{\delta_a}\delta_{a,max}$ for the rolling and stationary flight simulator as shown on the aforementioned figure. Values of $L_{\delta_a}\delta_{a,max}$ greater than 15 to 20 radians/sec^2 were not tested for the rolling simulator because of possible deficiencies in its dynamic response. A subsequent report figure will show the combination of variables covered in the in-flight investigation.

The test procedure used in this investigation was to have the pilot give a numerical rating for each of a given set of variables on the fixed simulator and on a rolling cockpit simulator. Unknown to the pilot, certain configurations were repeated in order to gain some insight as to the consistency of his ratings. As was noted previously, these simulator results were then compared with in-flight results. The reason the investigation was carried out in both a stationary and a moving simulator was that it was most expedient to study the basic approach to the solution of the problem through use of an available stationary simulator. Once it was shown that the approach was valid, it was felt that a repeat of the investigation on the moving simulator was justified in that these results should more closely duplicate flight results since the actual rolling motion would be impressed on the pilot. A useful by-product of the above procedure was that the results served to demonstrate, at least for the above type of investigation, the usefulness of a stationary flight simulator in spite of its inability to impart motion or accelerations to its occupant.

It should be pointed out that the pilots participating in this investigation had extensive flight test experience. They were for the most part seasoned test pilots with engineering educations and combat air veterans who have flown nearly all current Navy and Air Force operational fighter aircraft. In view of their level of experience, instructions to these pilots with regard to evaluation techniques were simply to rate the roll performance of a given airplane or a given simulated airplane configuration from the point that it was a current operational fighter aircraft and, as previously indicated, to assign a numerical rating according to a given schedule. This schedule, presented herein as table I, was modified from the pilot opinion schedule of reference 5. No specific fighter mission was assumed; however, the roll evaluation maneuvers included those which would be used by fighters carrying ballistic type weapons. The evaluation techniques used in flight by each of the pilots were similar and consisted essentially of two types of maneuvers. In the one case the pilot rolls the airplane as rapidly as is possible, or as is desired, through a bank angle change of not more than 270° while pulling g's. This is an evasive maneuver performed by a target airplane where a rapid change in flight path is most urgent and where precisely stabilizing at a given bank angle is unnecessary. The second can be classed as an attacking maneuver, where it is desired to roll on to and track a target. In this case the emphasis is on the ability to roll and to precisely stabilize at a given bank angle. The first maneuver is a test of the airplane's roll acceleration and roll rate capabilities and the second is a measure of what might be termed as precision of control and is an indication of the airplane's roll damping. The evaluation maneuvers used during the flight simulator runs were similar to those described above, with the limitation that no longitudinal motion was present. The flight simulation investigation was carried out using two evaluation pilots and the flight investigation was carried out using from one to four evaluation pilots per airplane.

RESULTS AND DISCUSSION

The first of the following sections will be concerned with a presentation of the data obtained from the flight simulator investigation, these data being given in terms of a roll performance criterion. The main contributing factors which determined the various pilot opinion boundaries of the roll criterion are presented and analyzed. The results of the flight simulator investigation are then compared with the actual flight-test results and the main differences in the two sets of data are briefly discussed. The final section is concerned with a cursory comparison of certain past and present roll performance concepts, with the roll performance criterion derived herein.

Fixed and Moving Flight Simulator Investigation

The data showing the relationship between pilot opinion of the lateral control and the parameter $L_{\delta_a}\delta_{a,max}$ for constant τ's for the fixed and rolling flight simulators are plotted in figures 9 and 10, respectively, and are tabulated in tables II and III. The solid lines shown in the figures were faired from an average of the averaged opinions of two pilots. It is inevitable that some scatter will exist in pilot opinion studies; however, for the case at hand it can be seen that the trends are well defined and the consistency of the pilots' ratings is considered to be good. On the other hand, it is believed that the inclusion of more evaluation pilots could make some changes in the curves. An additional factor which should be kept in mind is that the stick force and deflection characteristics were invariant throughout this phase of the investigation. It is probable that for most configurations tested, nominal changes in these values would not significantly affect the pilot ratings; however, this may not be true in the extreme region wherein high roll rates and high roll accelerations are attainable. In most cases the actual response of the rolling simulator closely duplicated the desired response; however, there were some deficiencies in the simulator response in that region where high angular accelerations were required, notably where $L_{\delta_a}\delta_{a,max} \gtrsim 10$ radians/sec². The influence of this factor on pilot opinion was not isolated; however, it is believed to be of secondary importance.

The relationship between pilot opinion and the parameters $L_{\delta_a}\delta_{a,max}$ and τ in terms of boundaries between the satisfactory-unsatisfactory regions, etc., for both the fixed and rolling simulator data is presented as figure 11. These curves were obtained from the previously presented averaged data. The pilot ratings which defined the various boundaries were as follows:

Satisfactory-unsatisfactory = pilot rating of 3-1/2
Unsatisfactory-unacceptable = pilot rating of 6-1/2

In addition, a curve corresponding to a pilot rating of 5 has been included in the figure. (A pilot rating of 5 corresponds to a description of unacceptable for normal operation.) It can be seen that the agreement between the boundaries as derived from the fixed simulator and the rolling simulator is excellent for $L_{\delta_a}\delta_{a,max} \lesssim 10$ radians/sec². This is a region where the maximum roll accelerations which can be impressed upon the pilot are not excessive. However, for $L_{\delta_a}\delta_{a,max}$ values greater than about 10 radians/sec² the roll simulator boundaries lie below those derived from the fixed simulator. The underlying reasons are that the forces on the pilot, which arise from the angular accelerations, hinder his ability to control precisely, with the resultant deterioration in pilot opinion as compared to a fixed simulator where no forces are present.

It should be noted that these pilot opinion regions of $L_{\delta_a}\delta_{a,max} \tilde{>} 10$ radians/sec^2 were in fact unsatisfactory or unacceptable because of the pilot's inability to control precisely during a rolling maneuver. For the region of long time constants and $L_{\delta_a}\delta_{a,max} \tilde{>} 10$ radians/sec^2 this was expected in view of theoretical results which show that a long time constant in the roll equation produced two closely related effects. First, as far as the pilot is concerned, the aileron becomes a roll acceleration rather than a roll rate control which human engineering studies (ref. 6) have indicated greatly increases the control difficulties of the human operator. The second effect is illustrated in figure 12. Here the computed aileron angles required to perform a given bank angle change for long and short time constants are plotted. It can be seen that for a short time constant the aileron motion required is a simple pulse, whereas for a long time constant the pilot must apply both a large upsetting aileron deflection and a large precisely timed restoring aileron deflection. This change in type of aileron motion appears to explain some of the problems of precision noted previously since, in attempting to perform such an aileron movement at high roll rates, the pilot might easily misjudge and overshoot the desired bank angle or get into an induced oscillation. A flight time history of a pilot's attempt to roll rapidly to a given bank angle and stabilize with an airplane having a large τ and large $L_{\delta_a}\delta_{a,max}$ value, which demonstrates the above point, is shown in figure 13. In the region of short time constants and high values of $L_{\delta_a}\delta_{a,max}$ it was reasoned that the pilot's reduction in precision of control was largely due to the extreme roll rates and roll accelerations which were encountered. His control difficulties in the over-all region of high $L_{\delta_a}\delta_{a,max}$ values were further compounded because of the extreme stick sensitivity in this region wherein small stick deflections commanded large roll rates and roll accelerations. On the other hand, the pilots rated the lower range of $L_{\delta_a}\delta_{a,max}$ values unsatisfactory or unacceptable because of the low roll rate and low roll acceleration capabilities of the test configurations. Because of the ability of the rolling simulator to impart motion to the evaluating pilot, it was felt, as was previously noted, the results from the rolling simulator were more akin to what would be obtained from an actual in-flight investigation and, therefore, all future discussion and comparisons will be confined to that set of data.

Comparison of Flight Test and Rolling Simulator Results

The region of roll parameters covered in the flight investigation is compared with the boundaries derived with the rolling simulator in figure 14. The parameters $L_{\delta_a}\delta_{a,max}$ and τ for each airplane were either computed from wind-tunnel measured or estimated values of $C_{l_{\delta_a}}$ and C_{l_p} and known mass and geometric characteristics or were measured

in flight according to the method outlined in appendix A. In order to cover as wide a flight test range of variables as possible, airplanes B and E were first flown with full normal aileron deflection available to the pilot; then temporary lateral stick stops were installed which reduced the available aileron deflection to one-half the normal amount. Airplane C was a variable-stability airplane capable of changing its roll characteristics through a wide range as can be seen from the subject figure. Airplane G was equipped with large wing tip tanks; however, these tanks were empty for the roll performance investigation. The remaining airplanes were flown in their normal clean condition.

Figure 15 was prepared so that a numerical pilot rating could be predicted from the moving simulator data for comparison with the results of the flight investigation. This figure consists of a sequence of contours beginning with a pilot rating contour of 2 and extending to 6-1/2. The dotted portion of a contour line indicates the contour was not well defined and hence is subject to some question. It will be noticed that there were no contours for a pilot rating of 1. This follows since the evaluation pilots seem to regard a pilot rating of 1, as representing an ideal or optimum configuration which could never really be attained.

Figure 16 is a comparison of the numerical pilot opinion ratings obtained from the flight investigation with those which would be predicted from the flight simulator results of figure 15. In figure 16 an arbitrary area has been defined, namely that region between the line of perfect correlation and the line of perfect correlation +1, wherein most of the actual pilot ratings lie. It is noteworthy that there were no cases wherein the actual pilot rating was appreciably better than the predicted value, and there were only three cases wherein the actual pilot ratings were greater than +1 away from that predicted. (In the case of airplane A, the pilots rated from a past recollection of roll performance rather than from a current flight evaluation.) The explanation for the poor prediction of pilot ratings for the other two test points is one which also explains the trend wherein the vast majority of actual pilot opinion ratings were somewhat greater than the predicted value. The principal argument is that the pilots' opinion of roll performance was adversely influenced by the coupling between the modes of motion which exist to some degree in all airplanes, but which for airplane D and for the low speed range of airplane F were excessive, and which the single-degree-of-freedom analysis used herein obviously does not take into account. However, for airplane F, as the speed was increased the rolling motions approached those described by a single-degree-of-freedom system and correspondingly (see fig. 16.) the actual pilot rating approached the predicted rating. Secondary factors which may have contributed to the above trend, wherein the actual rating was greater than the predicted, were objectionable control system dynamics and control system forces which may have been present.

In summary, from this flight investigation it can be seen that the roll performance criterion derived from rolling simulator tests would in most cases predict fairly accurately the pilot's opinion of the roll performance of fighter aircraft flying in their combat speed range. The predicted pilot opinion ratings, however, would be somewhat optimistic, depending upon the degree of coupling between the modes of motion. For the cases where a large amount of coupling exists, no such criterion can apply and, as previously noted, in such cases the basic trouble is a result of deficiencies in the dynamics of the other modes of motion which must be corrected before the roll performance can be predicted.

Comparison of Certain Roll Performance Concepts With the Derived Roll Performance Criterion

Figure 17 has been prepared in order to compare briefly the pilot opinion boundaries derived herein with the roll performance concept upon which the present military specifications for the lateral control of fighter aircraft are based. This concept, introduced in reference 1, is written in terms of the bank angle displacement occurring at the end of one second following an abrupt aileron input by the pilot. Curves of constant bank angle change at one second have been superimposed on the subject roll performance criterion and were computed using a ramp aileron input with a 0.2-second rise time. The flight tests showed that a pilot's attempted step aileron input can be approximated by such a ramp input. In addition, the relationship between τ, $L_{\delta_a}\delta_{a,max}$, and p_{ss} has been repeated in this figure for comparison with the pilot opinion boundaries.

The close correspondence between the pilot opinion boundaries located in the region of low $L_{\delta_a}\delta_{a,max}$ values and certain lines of constant bank angle change should be pointed out. When these curves are compared with the satisfactory-unsatisfactory pilot opinion boundaries it becomes obvious that a roll performance criterion based upon a single value of bank angle change, for example 50° or 100° in one second, would be invalid because it does not impose a roll damping requirement and because it does not recognize that aileron power in excess of that required to produce the given bank angle change could be detrimental. In the region of low $L_{\delta_a}\delta_{a,max}$ values and for $\tau \lessapprox 0.7$ second it can be seen that there are lines of constant p_{ss} which are also coincident with the pilot opinion boundaries. This was expected in view of pilot comments which, as was previously pointed out, indicated that these boundaries were determined principally from the roll rate capabilities of the configuration.

The validity of the wing tip helix angle, $p_{ss}b/2V$, as a roll performance criterion will be discussed briefly. This is considered apropos in view of the historical role this parameter has played in the lateral control design of aircraft, reference 2, and in view of the fact that

currently the roll performance of fighters, bombers, transport, and trainer-type aircraft is, within certain speed ranges, designed in terms of certain constant values of this parameter.

From the flight simulator ratings it was surmised that a constant $p_{ss}b/2V$ value could not be used as a general measure of roll performance of fighter-type aircraft flying in their combat speed range. This follows from the argument that, in essence, there is a one to one correspondence between the pilot opinion ratings and the points on the $L_{\delta_a}\delta_{a,max}$-$\tau$ plane. However, for any given point on this plane there corresponds numerous $p_{ss}b/2V$ values, and hence pilot opinion is not dependent on $p_{ss}b/2V$.

In spite of the above argument against $p_{ss}b/2V$ as a general measure of roll performance, it is true that in certain restricted cases, and as past studies have indicated, pilot opinion will correlate with this parameter. This follows from figure 17, where it was shown that the derived pilot opinion boundaries located in the region of low $L_{\delta_a}\delta_{a,max}$ values and for $\tau \tilde{<} 0.7$ second are coincident with certain lines of constant p_{ss}. If we restrict ourselves to a given era of fighter aircraft, for example World War II vintage, which have roughly the same wing span and speed capabilities and for which the roll time constant was less than 0.7 second, then the combination of their average span, combat velocity, and a specified value of p_{ss} would result in a value of $p_{ss}b/2V$ which would correlate with pilot opinion of fighter roll performance. However, the current trend for fighter aircraft to have τ's > 0.7 second and to exhibit quite large differences in wing span length, speed capabilities, etc., invalidates the wing tip helix angle as a roll performance criterion.

As a matter of interest the flight test pilot opinion data have been plotted against $p_{ss}b/2V$ in figure 18. The fairly strong correlation of pilot opinion with $p_{ss}b/2V$ for the variable-stability airplane, C, is evident and was expected in view of the fact that the range of stability tested was that of airplanes having different roll rate capabilities but with $\tau < 0.7$ second and having the same wing span length and same combat speed. If the totality of flight test points is considered, it can be seen that no strong correlation exists. In view of this discussion it is reasoned that in the case wherein the roll performance of bombers, etc., is considered, a possible deficiency in the use of wing tip helix angle as a measure of roll performance might also exist. This, of course, is based on conjecture and should be an area for further research.

CONCLUSIONS

Pilot opinion of the roll performance of fighter-type aircraft has been compared with the results of a flight simulator investigation. The simulators used in this study consisted of a rolling cockpit or a stationary cockpit and an electronic analog computer for solving the equations of motion. The cockpit provided means for including the pilot in the control loop. From this study the following conclusions were made.

1. It was deduced and demonstrated on the simulators that pilot opinion of the lateral controllability of fighter-type aircraft would correlate with a roll damping parameter and an aileron power parameter which was written in terms of roll acceleration. In addition, boundaries in terms of these two parameters were determined for satisfactory, unsatisfactory, and unacceptable roll performance.

2. From the flight investigation it was concluded that the roll performance criterion derived from the rolling simulator will give a fairly accurate prediction of the actual in-flight pilot opinion, provided the degree of coupling between the airplane modes of motion was not excessive.

3. As a result of this study, it appears that the bank angle change at the end of 1 second following an abrupt aileron input by the pilot is deficient as a specification covering the lateral controllability of fighter aircraft flying in their combat speed range. This is principally because the specification fails to impose a roll damping requirement and because it does not recognize that an excess of aileron power can be detrimental.

4. The results of this study would indicate that the wing tip helix angle could not be used as a general measure of the roll performance of fighter-type aircraft flying in their combat speed range.

5. As a by-product of this study it was found that the fixed simulator results were in close agreement with the flight and rolling simulator results, provided the roll accelerations which could be impressed upon the pilot were not large. However, if the angular accelerations which could be impressed upon the pilot were high, the results tended to differ, the reason being that in this region the forces impressed upon the pilot in the moving simulator or in flight hindered his ability to control as compared to the fixed cockpit where no forces were present.

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APPENDIX A

METHOD USED TO DETERMINE τ AND $L_{\delta_a}\delta_{a,max}$ FROM FLIGHT TEST

The simplified technique for determining the airplane rolling time constant, τ, and aileron power, $L_{\delta_a}\delta_{a,max}$, from flight tests, neglects effects of airframe flexibility. The airplane roll equation, wherein the two subject parameters appear which has been derived in reference 7, may be written as follows:

$$\dot{p} = \frac{I_{xz}}{I_x}(\dot{r}+pq) + \left(\frac{I_y-I_z}{I_x}\right)qr + L_{\delta_a}\delta_a + L_p p + L_\beta \beta + L_r r + \ldots \qquad \text{(A1)}$$

where

C_{l_β} — $\dfrac{\partial C_l}{\partial \beta}$, per radian

C_{l_r} — $\dfrac{\partial C_l}{\partial (rb/2V)}$, per radian

I_{xz} — product of inertia about X, Z body axes, slug-ft^2

I_y — moment of inertia about the Y body axis, slug-ft^2

I_z — moment of inertia about the Z body axis, slug-ft^2

L_β — $\dfrac{\bar{q}Sb}{I_x} C_{l_\beta}$, per sec^2

L_r — $\dfrac{\bar{q}Sb^2}{2VI_x} C_{l_r}$, per sec

q — pitching velocity, radians/sec

r — yawing velocity, radians/sec

β — sideslip angle, radians

All remaining terms are defined in the notation section of the text.

It should be noted that in the above equation only the principal aerodynamic terms are included and that $L_p = -1/\tau$.

Provided the airplane modes of motion are not strongly coupled, the response from a level flight trim condition following an aileron deflection is approximated, at least for the first few seconds of transient motion, by the following equation,

$$\dot{p} = L_{\delta_a}\delta_a + L_p p \tag{A2}$$

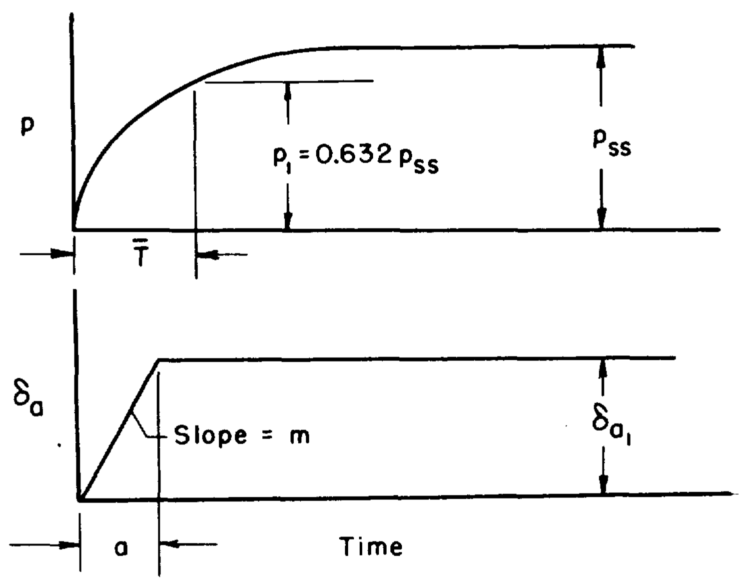
This follows from equation (A1) since for the pure aileron maneuver being considered, the quantities $\dot{r}$, r, q, and β are small and for fighter airplanes the following relationships are in most cases true

$$L_r \ll 1, \qquad \frac{I_{xz}}{I_x} \ll 1, \qquad \frac{I_y - I_z}{I_x} < 1$$

Hence the terms, $\frac{I_{xz}}{I_x}(\dot{r}+pq)$, $\left(\frac{I_y-I_z}{I_x}\right)qr$, $L_\beta\beta$, and $L_r r$, which are composed of the product of two small numbers, are considered to be negligible.

Ideally, the flight maneuver from which the parameters $L_{\delta_a}\delta_{a,max}$ and τ could most easily be extracted, using the relationship of equation (A2) would be a response to a pure aileron step input. However, this type of input is not possible because of the pilot's finite time lag and limited power capability. Examination of flight records wherein the pilot attempted to make a step input shows that the resulting stick motion approximates a ramp. Hence, the following procedure will be limited to the response to a ramp input of the system governed by equation (A2).

For a ramp input, the resulting motion is as follows:



and is described by the following equation:

for $0 \leq t < a$

$$p = \tau^2 L_{\delta_a} m \left(e^{-\frac{t}{\tau}} + \frac{t}{\tau} - 1\right) \tag{A3a}$$

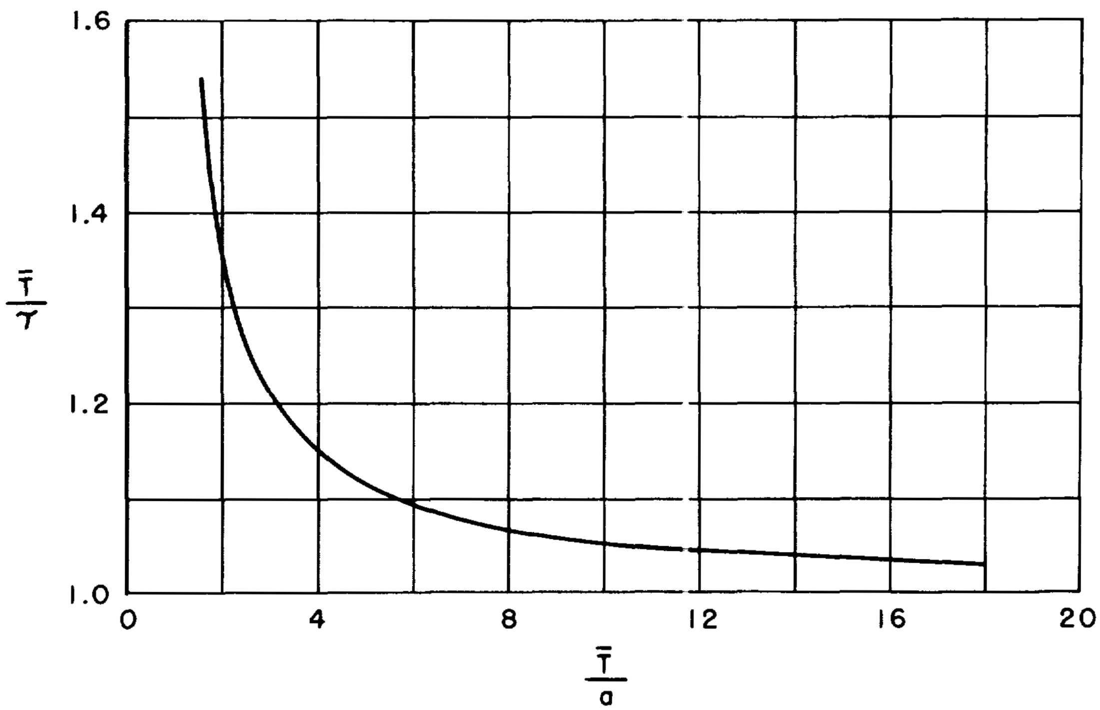
and for $t \geq a$

$$p = \tau^2 L_{\delta_a} m \left[e^{-\frac{t}{\tau}} \left(1 - e^{\frac{a}{\tau}}\right) + \frac{a}{\tau}\right] \tag{A3b}$$

Now for the given input and response we can measure a pseudo time constant, $\overline{T}$, which is defined in the same fashion as the true time constant, namely the time for the roll rate to reach 0.632 of its steady-state value. Now, if we assume that $\overline{T} > a$ (which was true for all the subject flight tests) we can write, using equation (A3b), the ratio of $p_{ss}/p(\overline{T})$. This results in a unique relation between a, $\overline{T}$, and the true time constant of the system, τ, and may be written as follows:

$$\frac{\overline{T}}{\tau} = ln \left(\frac{1 - e^{\frac{a}{\tau}}}{-0.368 \frac{a}{\tau}}\right) \tag{A4}$$

and which can be plotted as shown in the following sketch.

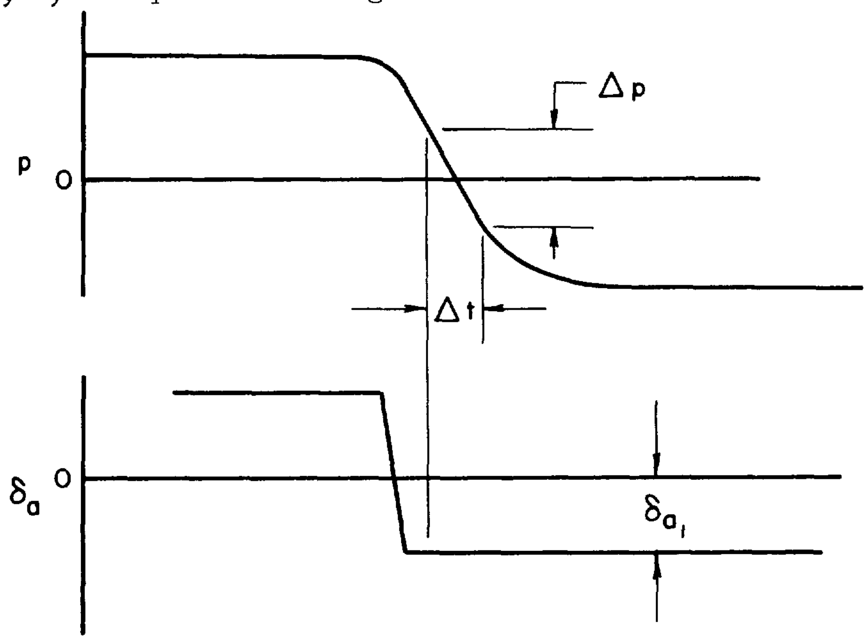


From a flight time history of the airplane roll response and corresponding ramp aileron input, we can measure a, δ_{a_1}, $\overline{T}$, and p_{ss}, and hence τ can be immediately determined from the preceding plot. From equation (A3b) we can obtain the following relationship:

$$p_{ss} = \tau L_{\delta_a}\delta_{a_1} \tag{A5}$$

With the aid of this equation we can obtain $L_{\delta_a}\delta_{a_1}$, and by linear extrapolation we can arrive at $L_{\delta_a}\delta_{a,max}$.

There is a likelihood of some error occurring in the measured value of $L_{\delta_a}\delta_{a,max}$ because it depends upon p_{ss}, which can only be measured late in the time history. Hence the aileron power may be influenced by those terms deleted from equation (A1) which were considered to have only a minor influence at the beginning of the transient response. In view of this an additional check of $L_{\delta_a}\delta_{a,max}$ could be made by allowing the airplane to reach a steady-state rolling velocity and then rapidly reversing the aileron input as pictured below. The pilot is asked to keep the value of β, r, and q small during this maneuver.



Now from equation (A1), it can be deduced that at the time $p = 0$, the following relationship holds:

$$L_{\delta_a}\delta_{a_1} = \frac{\Delta p}{\Delta t}$$

Hence a value for $L_{\delta_a}\delta_{a,max}$ can be determined by linear extrapolation.

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4. Gardner, Murray F., and Barnes, John L.: Transients in Linear Systems Studied by the Laplace Transformation. Vol. 1, John Wiley and Sons, Inc., N. Y., 1942.

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6. Hick, W. E., and Bates, J. A. V.: The Human Operator of Control Mechanisms. Permanent Records of Research and Development, No. 17.204, May 1950.

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TABLE I.- PILOTS' RATING SCHEDULE

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

TABLE II.- FIXED SIMULATOR PILOT RATINGS

τ, sec	$L_{\delta_a}\delta_{a,max}$, radians/sec^2	Pilot A ratings						Pilot B ratings		
		Evaluation no.						Evaluation no.		
		1	2	3	4	5	6	1	2	3
0.1	0.35	10								
	.7	9-1/2						9		
	1.5	7-1/2						9		
	3	6						8	7	
	6	4						6	7	
	10	3						4	3	
	15	2						3		
	20	1						2+		
	30	1						1	1	
	40	1+						1		
	60	2						2 or 3		
.2	.2	8						9		
	.35	6-1/2						9		
	.5	6								
	.7	6						9	8 or 9	
	1.5	5-1/2	6					7		
	3	4-1/2						5		
	4	4						4	4 or 5	
	6	3-1/2						3	4	3 or 4
	10	2-1/2	1-1/2					2	3	
	15							1		
	20	1	1-1/2					2 or 3	1 or 2	2
	30	2-1/2								
	35	2+								
	40	3-1/2								
.4	.35	6-1/2						7		
	1.5	5						5		
	3	4+						3		
	6	3						2	3 or 4	
	10	2+	2+					2 or 3	3	3 or 4
	15	3						3		
	20	4						5 or 6	4 or 5	
	30							5 or 6		
	40							7		
1	.1375	8								
	.5	5-1/2						8		
	1	5+	5+							
	1.5	5-	4-1/2					5		
	3	3-1/2	3-1/2	3-1/2				3		
	4	3-						4		
	6	3	3+	4	4	3		3	4	
	10	3-1/2	3-1/2	4	4+	4+	3-1/2	4		
	15	5	4+					6		
	20	5-1/2	6	5				4 or 5	7	7
	25	6-1/2	6							
	30	8	7	7				8	8 or 9	
2	.2	6								
	.5	5-						7		
	1	3-1/2	4-1/2					6		
	2	3+	4-							
	2.5	3-1/2								
	3	3-1/2						4 or 5		
	6	4-1/2	4+	5				5		
	10	6-1/2	6					6	6	
	15	7-1/2						6		
	20	8						7		
	30	8						8 or 9		
4	.15	6-1/2						8		
	.5	5						7		
	1	4						6		
	2	3-1/2						6		
	3	3	4-							
	4	4						5		
	6	5	5					5	5 or 6	
	10	6-1/2	5-1/2					5+	5 or 6	
	12	6	6-1/2							
	15	8-						6	7	
	20	8						8 or 9		
	30	8-1/2								

TABLE III.- ROLLING SIMULATOR PILOT RATINGS

τ, sec	$L_{\delta_a}\delta_{a,max}$, radians/sec^2	Pilot A ratings				Pilot B ratings		
		Evaluation no.				Evaluation no.		
		1	2	3	4	1	2	3
0.1	0.35	8-1/2				10		
	.7	8-1/2				9		
	1					7 or 8	8	
	1.5	7+				8		
	2	6-1/2				6	6	
	3	6-1/2				5	6	
	6	5				5	5	
	10	4+				4		
	15	3-				3		
	20	2				3		
	30	3-1/2				2		
.2	.2	8-1/2						
	.35	8-1/2				10		
	.7	8-				9	7	7 or 8
	1	6				7	8	
	1.5	5				6		
	2					6		
	3	4-1/2				5 or 6		
	4					3 or 4		
	6	3-1/2				4	3	4 or 5
	8	3						
	10	2-1/2	2+			2	3	
	15	2+	1-1/2			2		
	20	4-1/2	2-1/2					
.4	.15	8-1/2				10		
	.35	7				8	7	
	.7	6	6-1/2	6		6	5 or 6	6
	1	5-1/2				6	5	
	1.5					5		
	2	4+				4 or 5		
	3	3				3		
	4					3		
	6	2-				1	2 or 3	3
	10	2+	2			1 or 2		
	15	4	3			5	4	
	20	6						
1	.15	8				8	7	
	.35	6				6	6	
	.70	5				5-	5	
	1	4-1/2	5			5	4 or 5	
	2	3-1/2	4			5		
	3	4	4	3-1/2		3 or 4	4	
	4	3+				3		
	5	2-1/2						
	6	2+				2 or 3	2	
	8					4		
	10	5	4+			5		
	15	8	5-1/2			8	6	
2	.15	8				7		
	.2	7-						
	.35	5				6	5 or 6	
	.5	6-						
	.7	5	5-1/2	5-1/2		4 or 5	5	
	1	4-	5			4	4 or 5	
	1.5	4+	4-1/2	4+				
	2	3+	4-	4		4		
	3	3-1/2				4		
	4					4		
	6	5+				3		
	7.5	4+						
	8					4		
	10	6-1/2				6		
4	.15	6-1/2	7			7		
	.2	6-1/2						
	.35		6-1/2	7-		6	5	
	.50	6						
	.7	6	6			5	5	
	1	5	4-1/2	5	5-1/2	4	5	
	1.5	5	4+					
	2	5-	4			6	4	
	3	4				5	4	
	3.75	5						
	4					5		
	6	5				6	4	
	10	7				6		

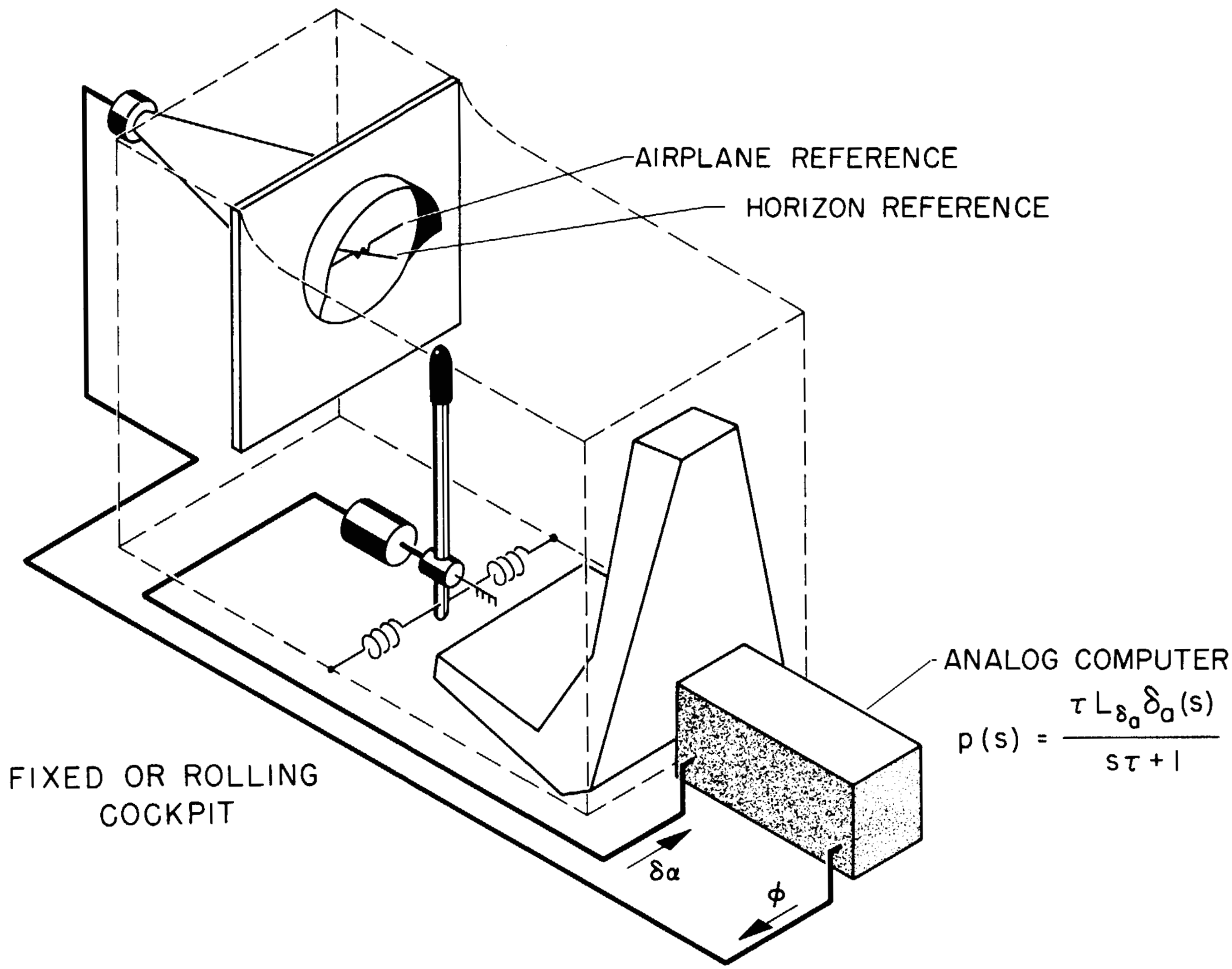
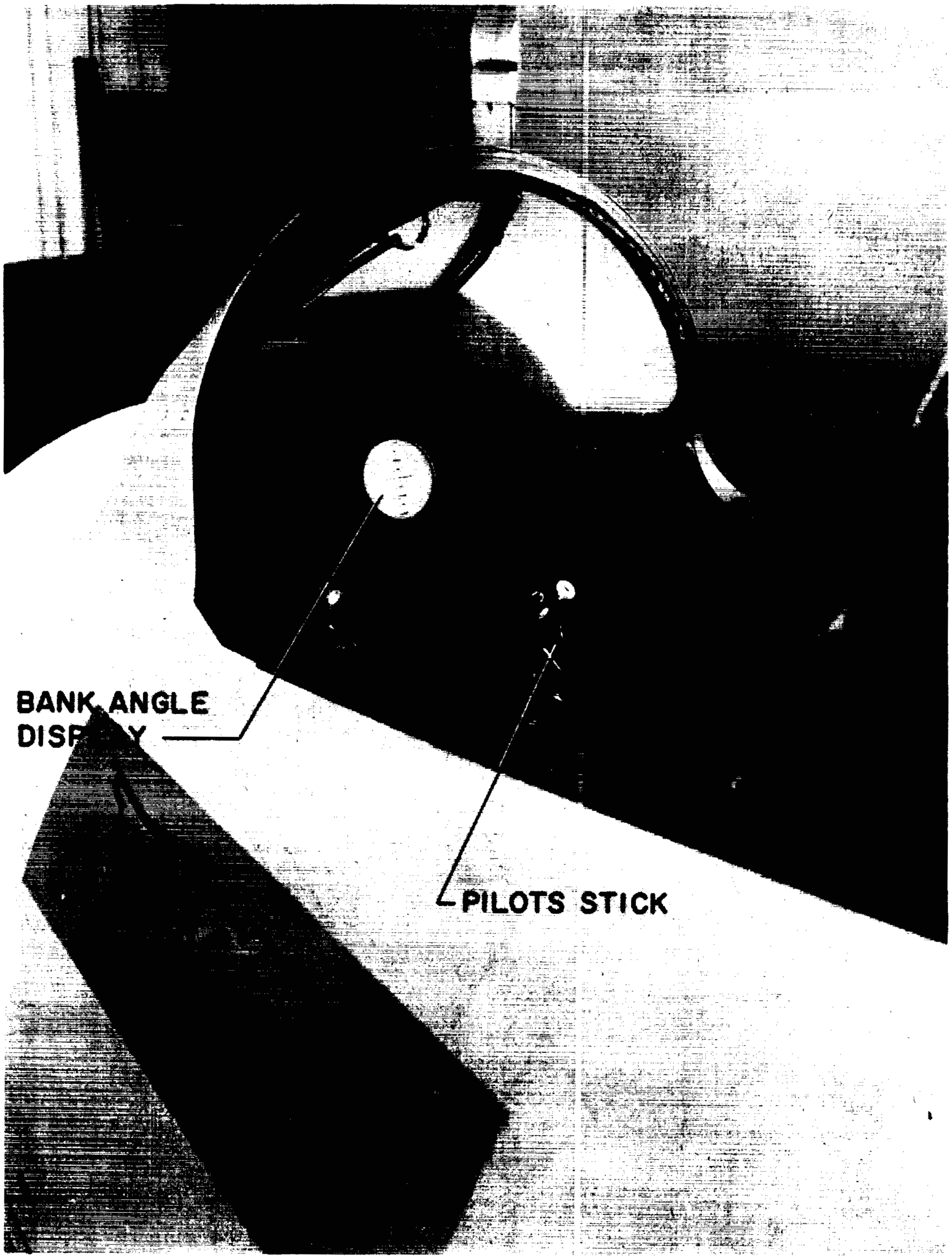
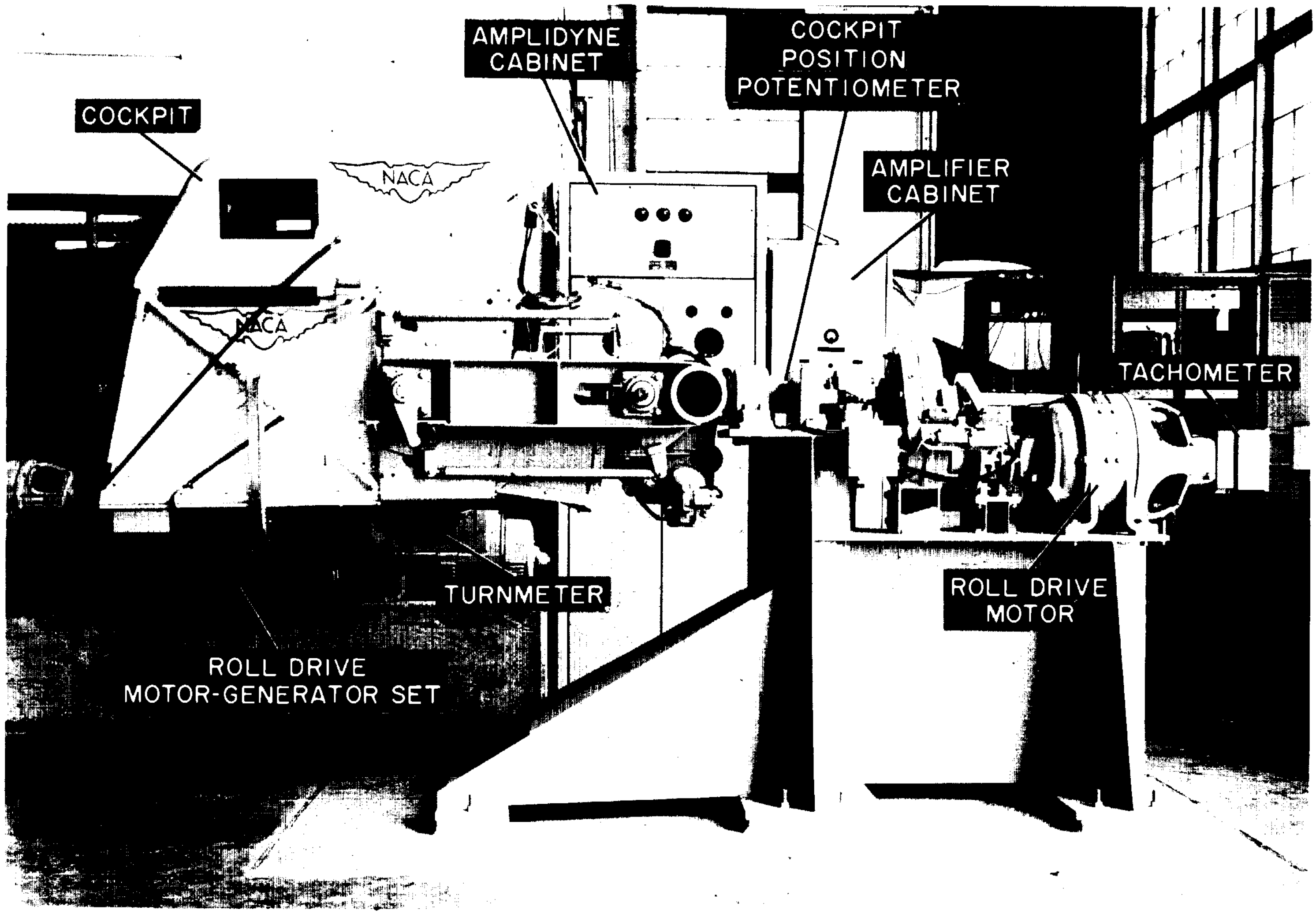


Figure 1.- Diagram showing flow of information for flight simulator.



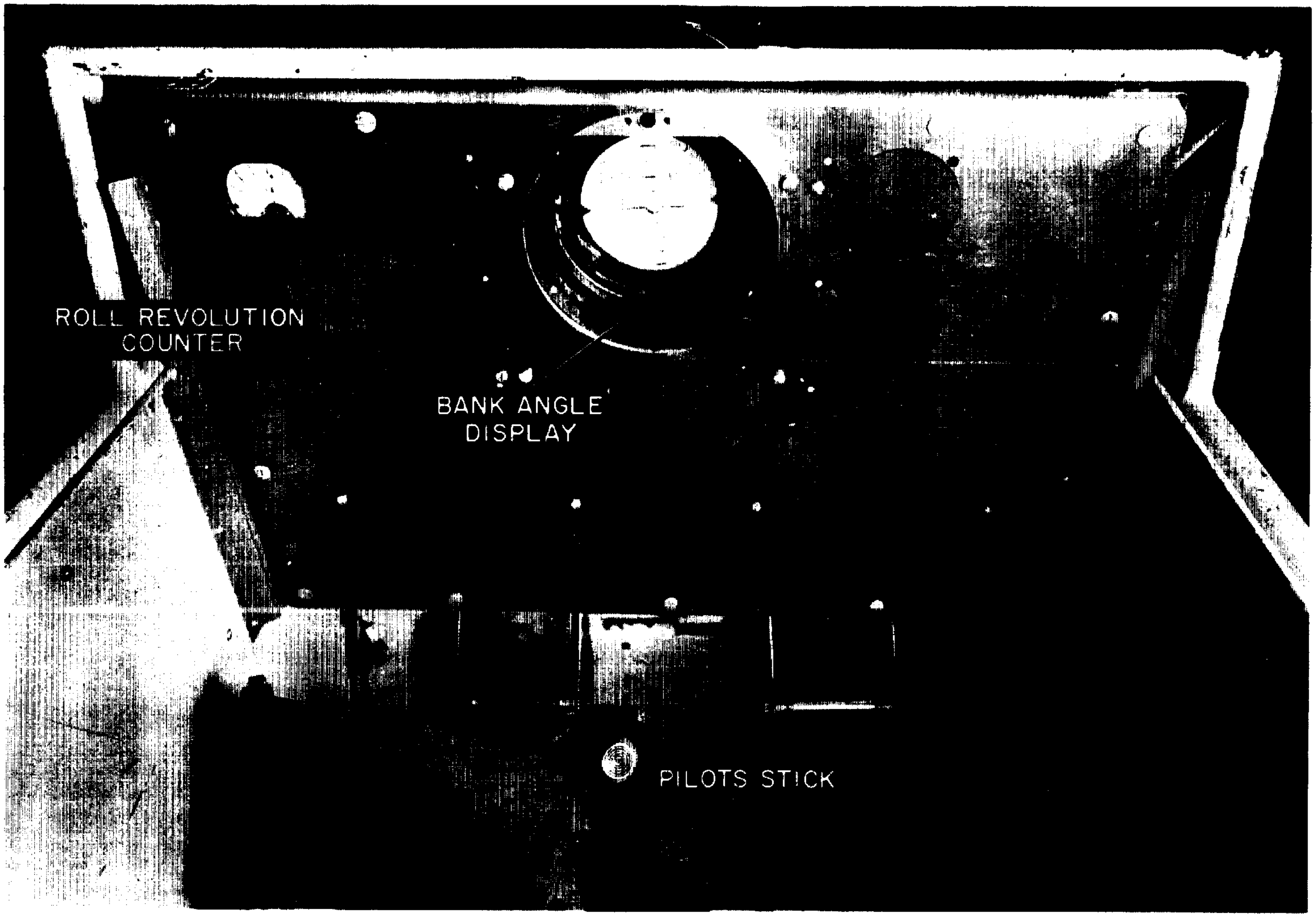
A-23010.2

Figure 2.- Fixed cockpit and pilot's instrument display.



(a) View of cockpit exterior.

Figure 3.- Views of moving simulator.



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(b) View of cockpit interior.

Figure 3.- Concluded.

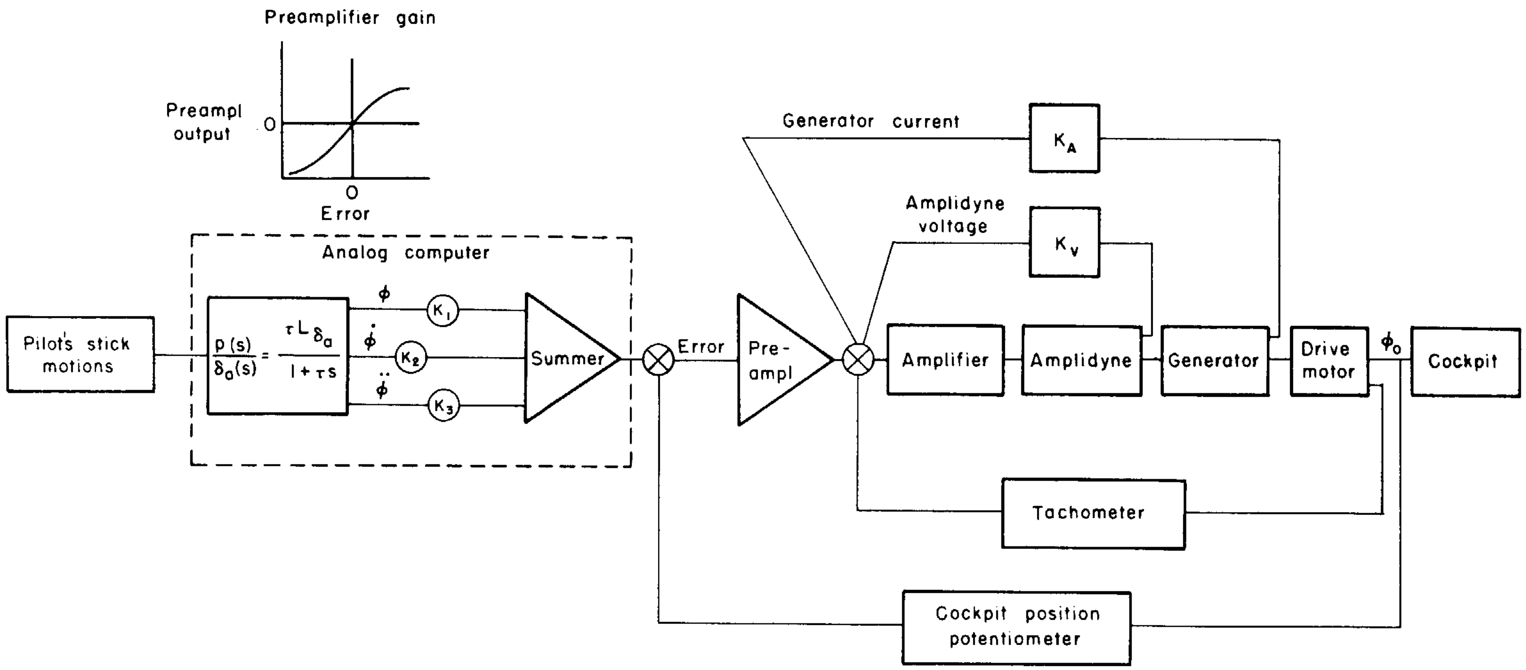


Figure 4.- Block diagram of roll drive system.

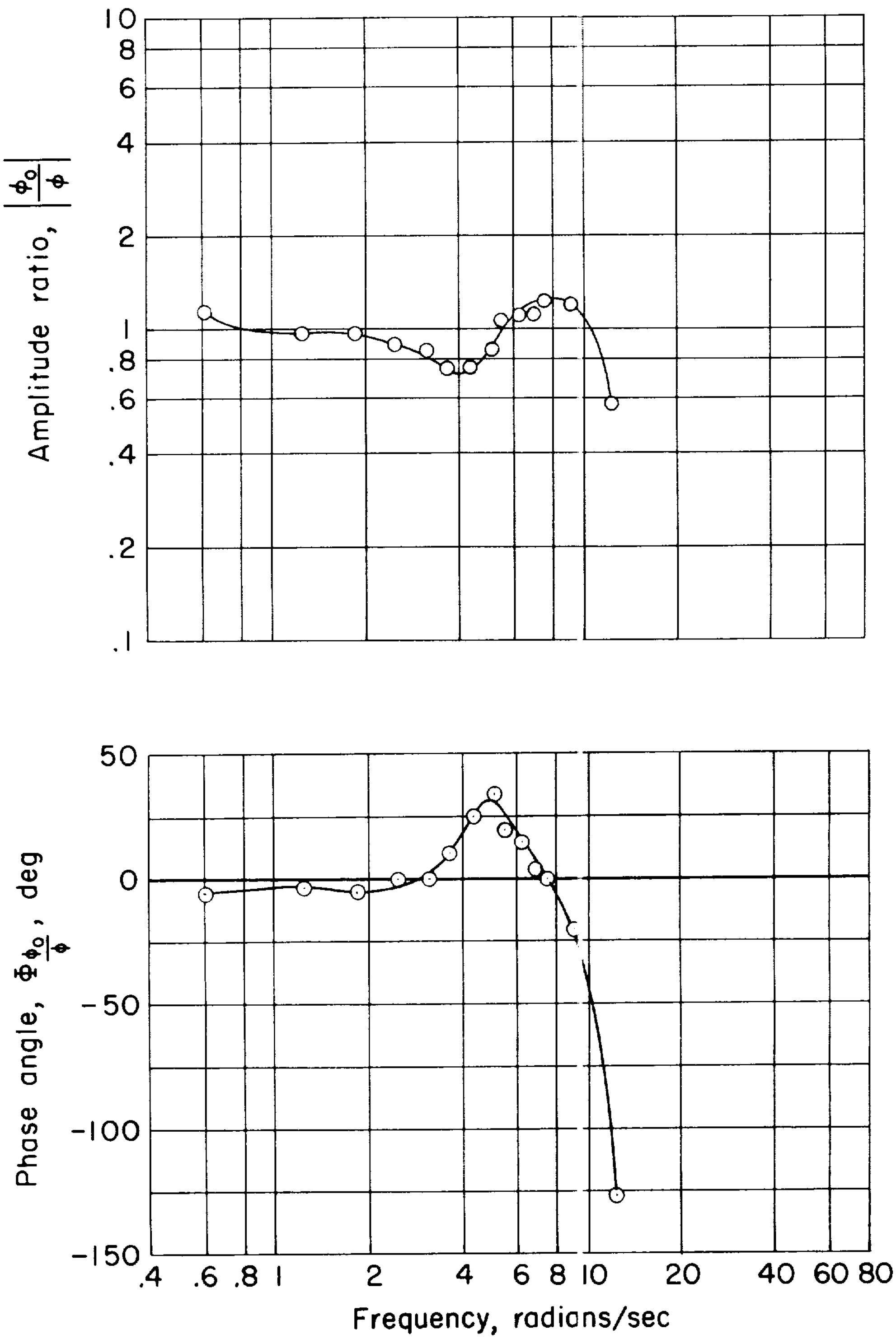


Figure 5.- Frequency response of the roll drive servo system.

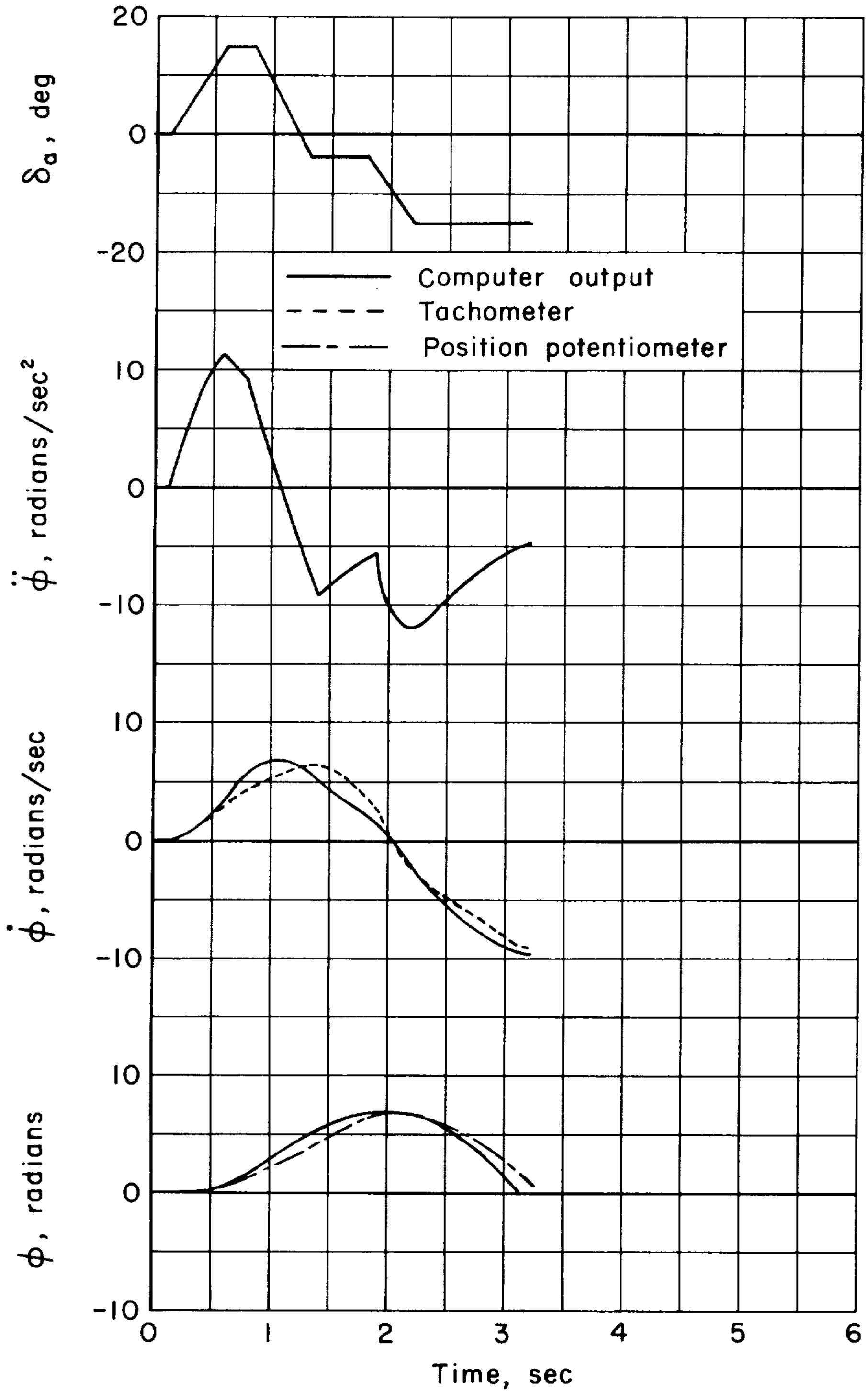
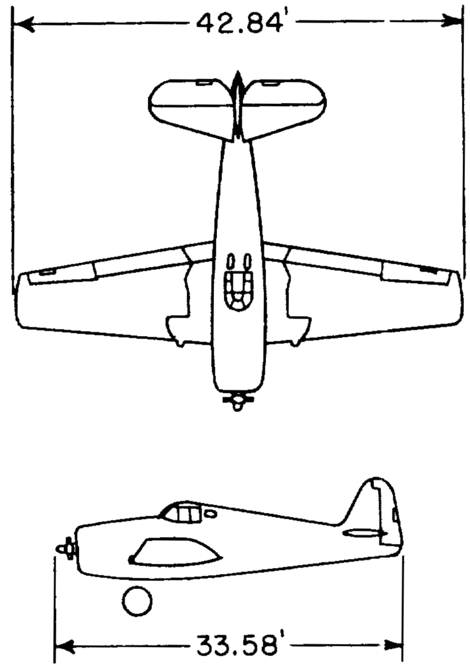
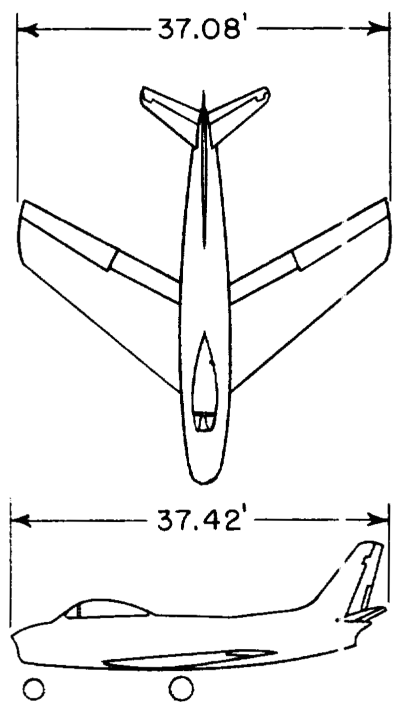


Figure 6.- Time history comparing the moving simulator motions with computed motions for ramp aileron inputs with $\tau = 1.0$ second and $L_{\delta_a}\delta_{a,max} = 15$ radians/sec^2.

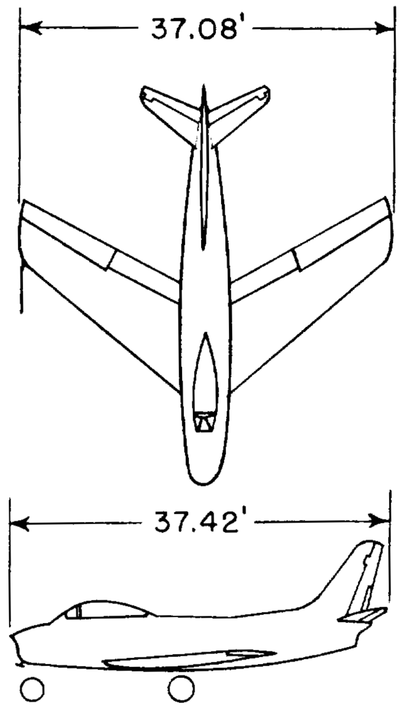


(a) Airplane A.

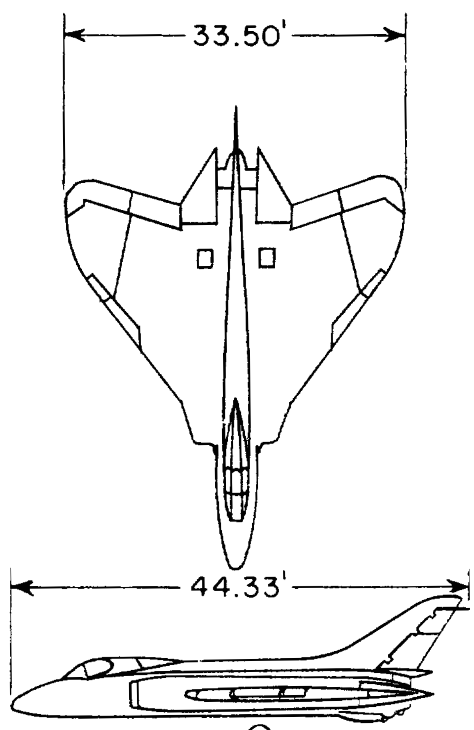


(b) Airplane B.

Figure 7.- Airplanes tested during flight investigation.

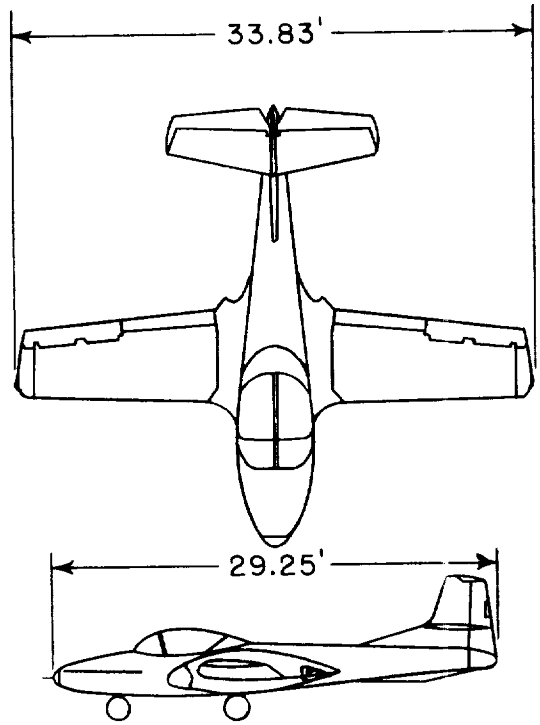


(c) Airplane C.

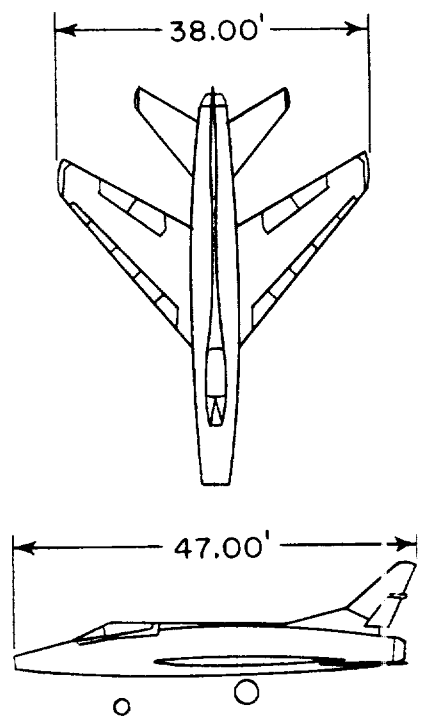


(d) Airplane D.

Figure 7.- Continued.

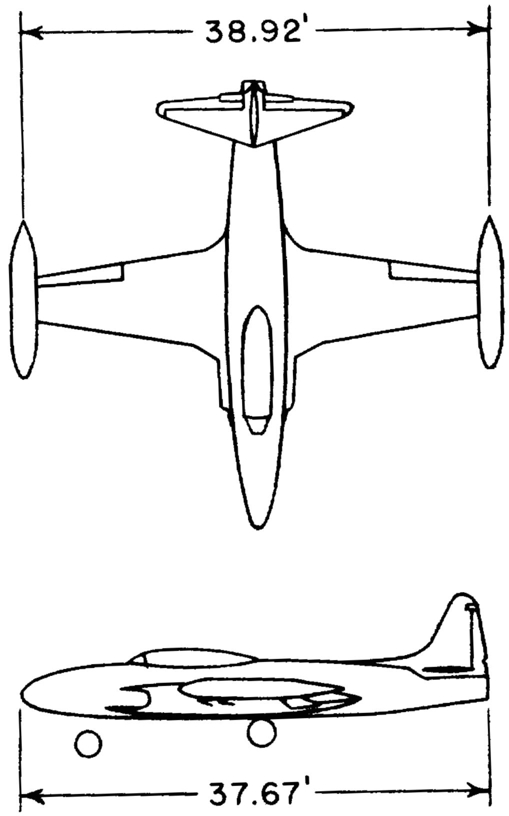


(e) Airplane E.



(f) Airplane F.

Figure 7.- Continued.



(g) Airplane G.

Figure 7.- Concluded.

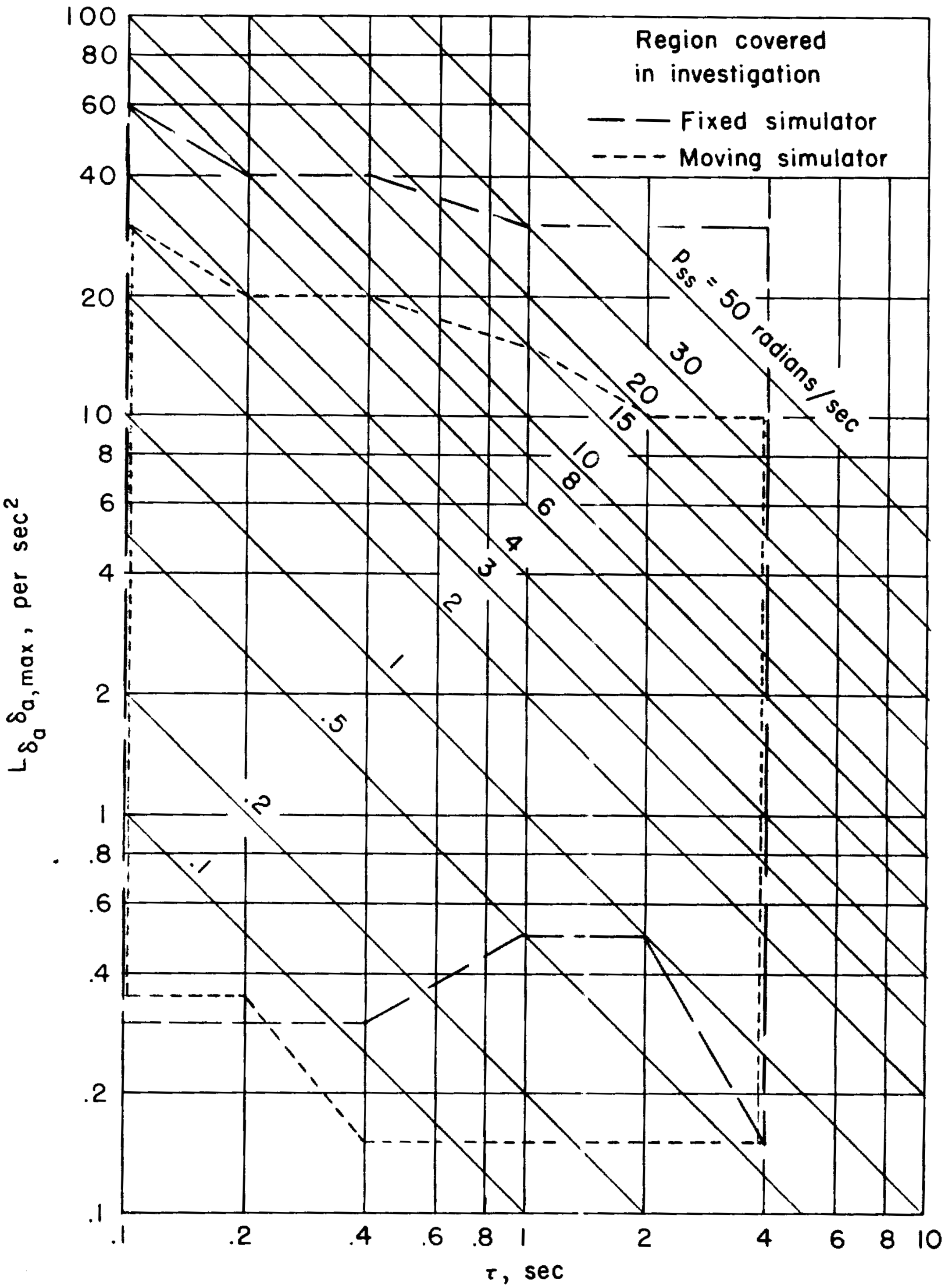


Figure 8.- Variation of p_{ss} with τ and $L_{\delta_a}\delta_{a,max}$ and range of parameters covered in the flight simulator investigations.

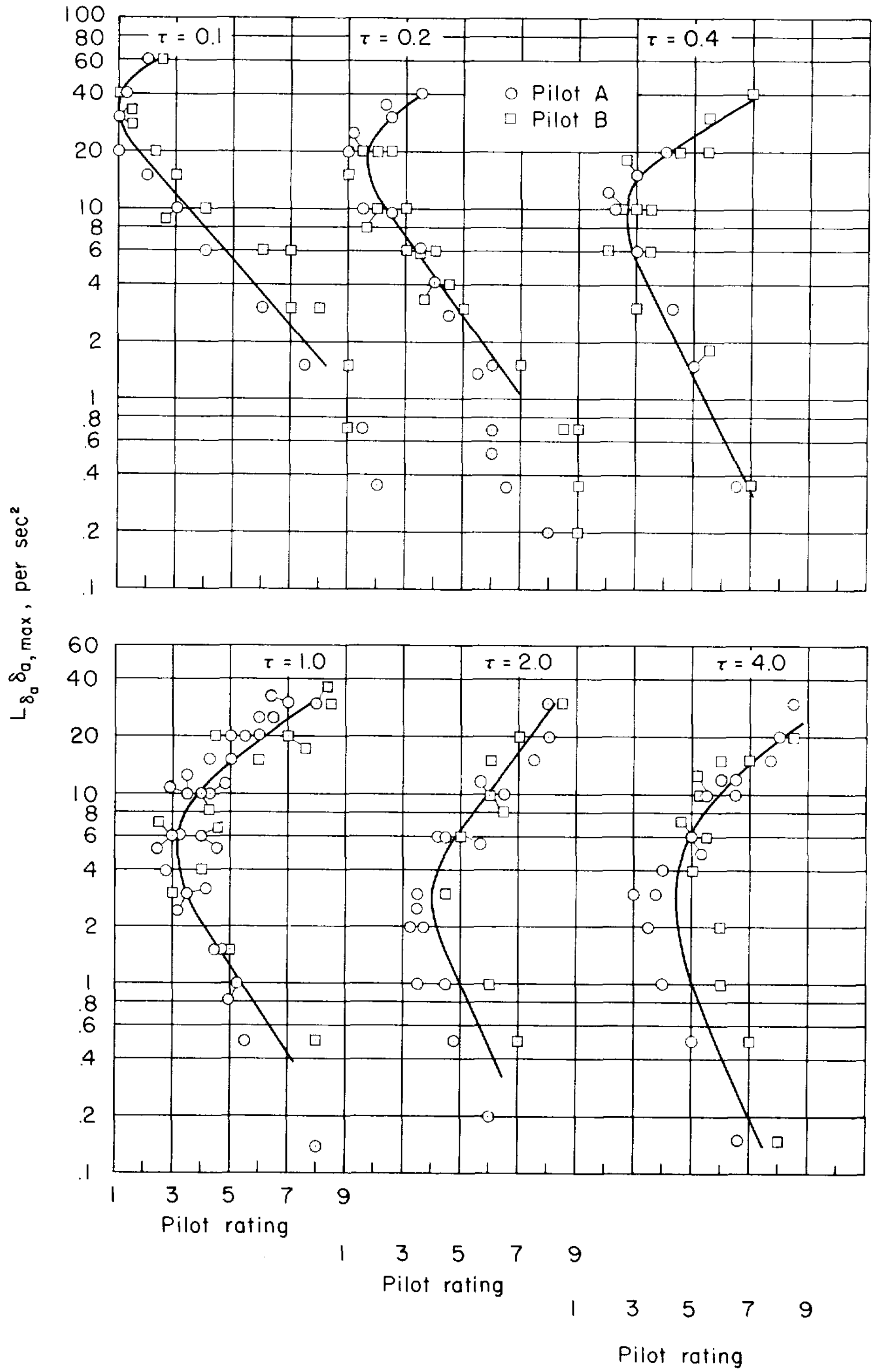


Figure 9.- Variation of pilot opinion with $L_{\delta_a}\delta_{a,max}$ for constant values of τ as obtained from the stationary flight simulator.

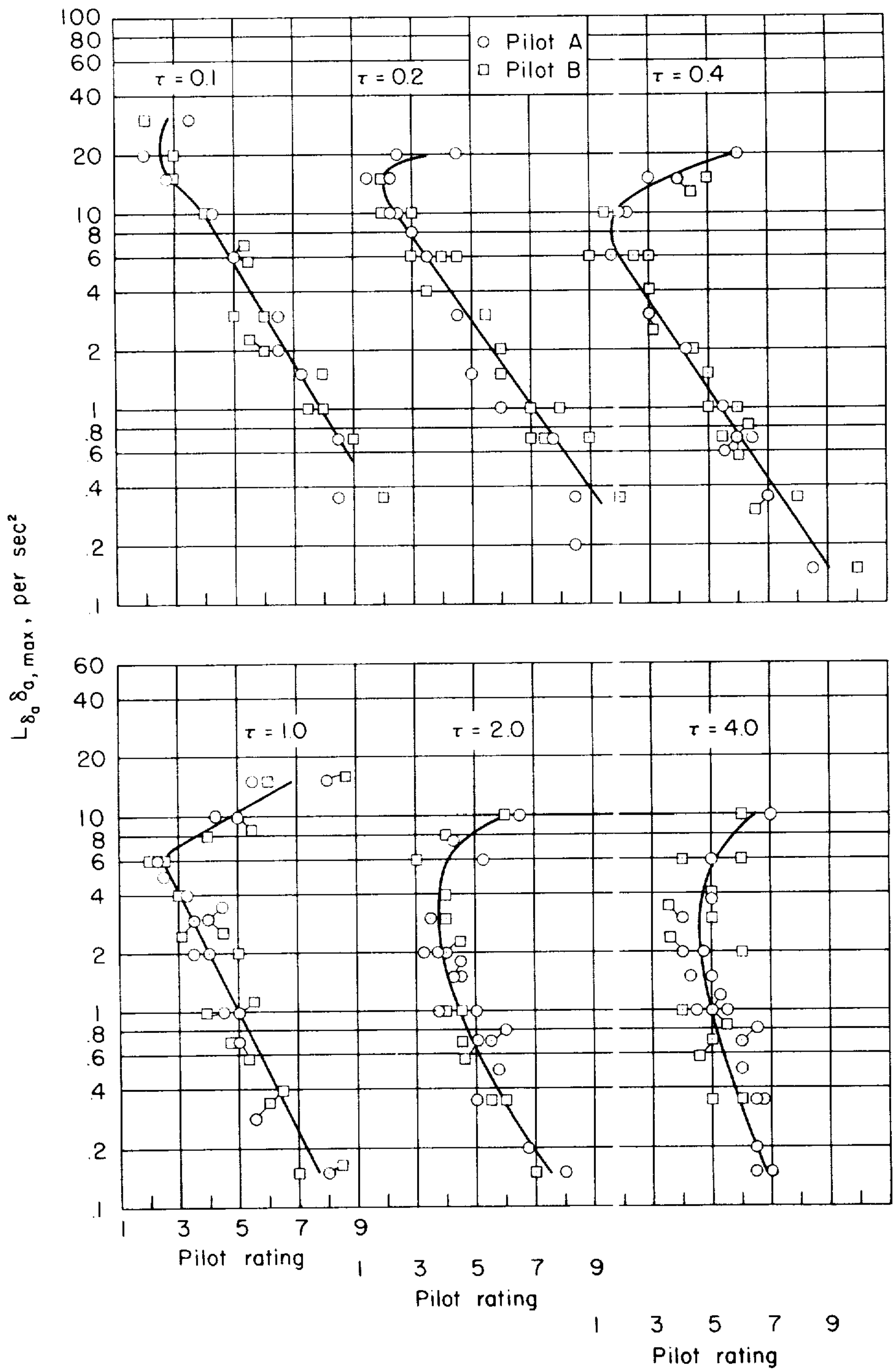


Figure 10.- Variation of pilot opinion with $L_{\delta_a}\delta_{a,max}$ for constant values of τ as obtained from the moving flight simulator.

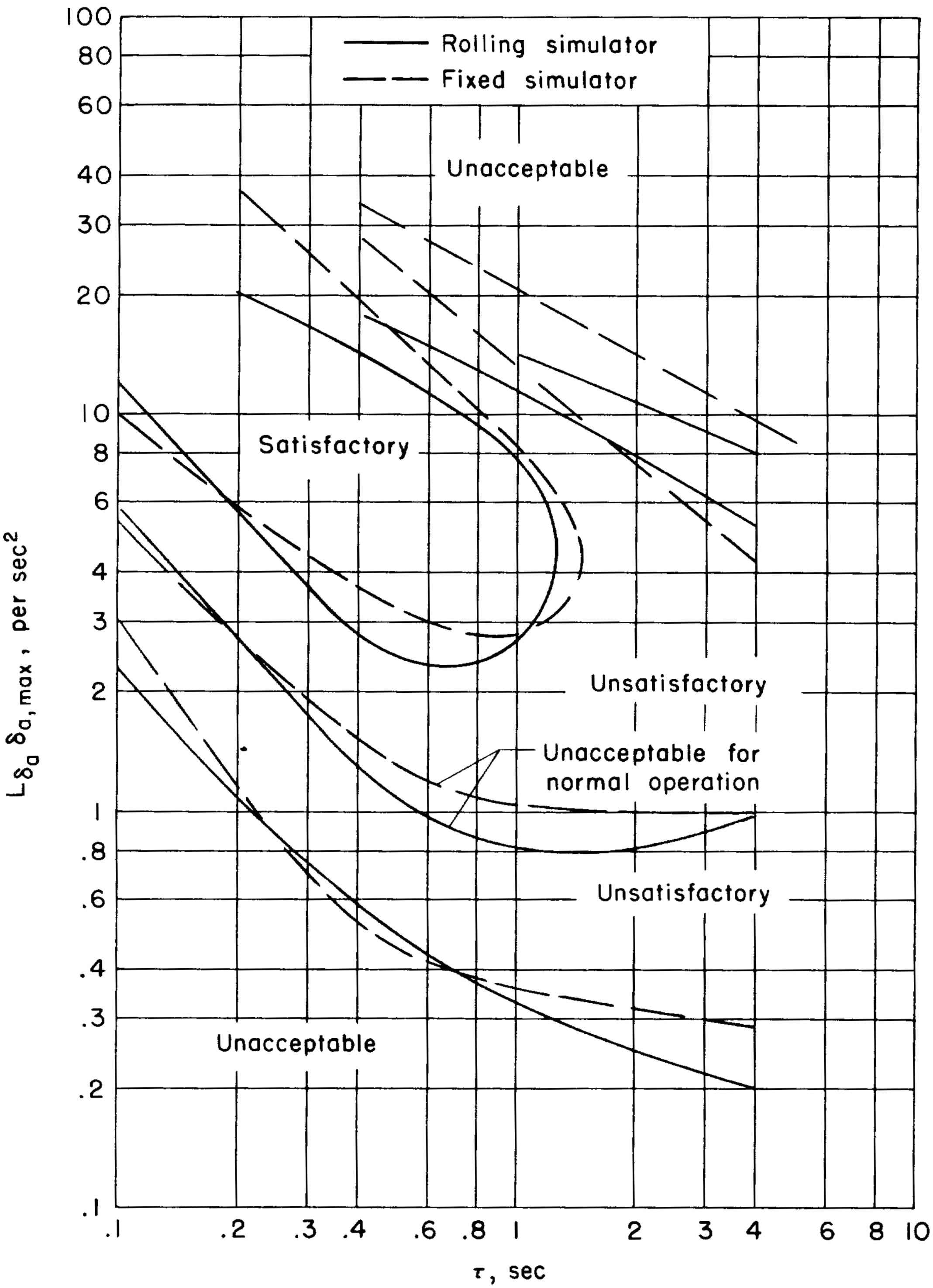


Figure 11.- Comparison of pilot opinion boundaries obtained from the fixed and moving flight simulators.

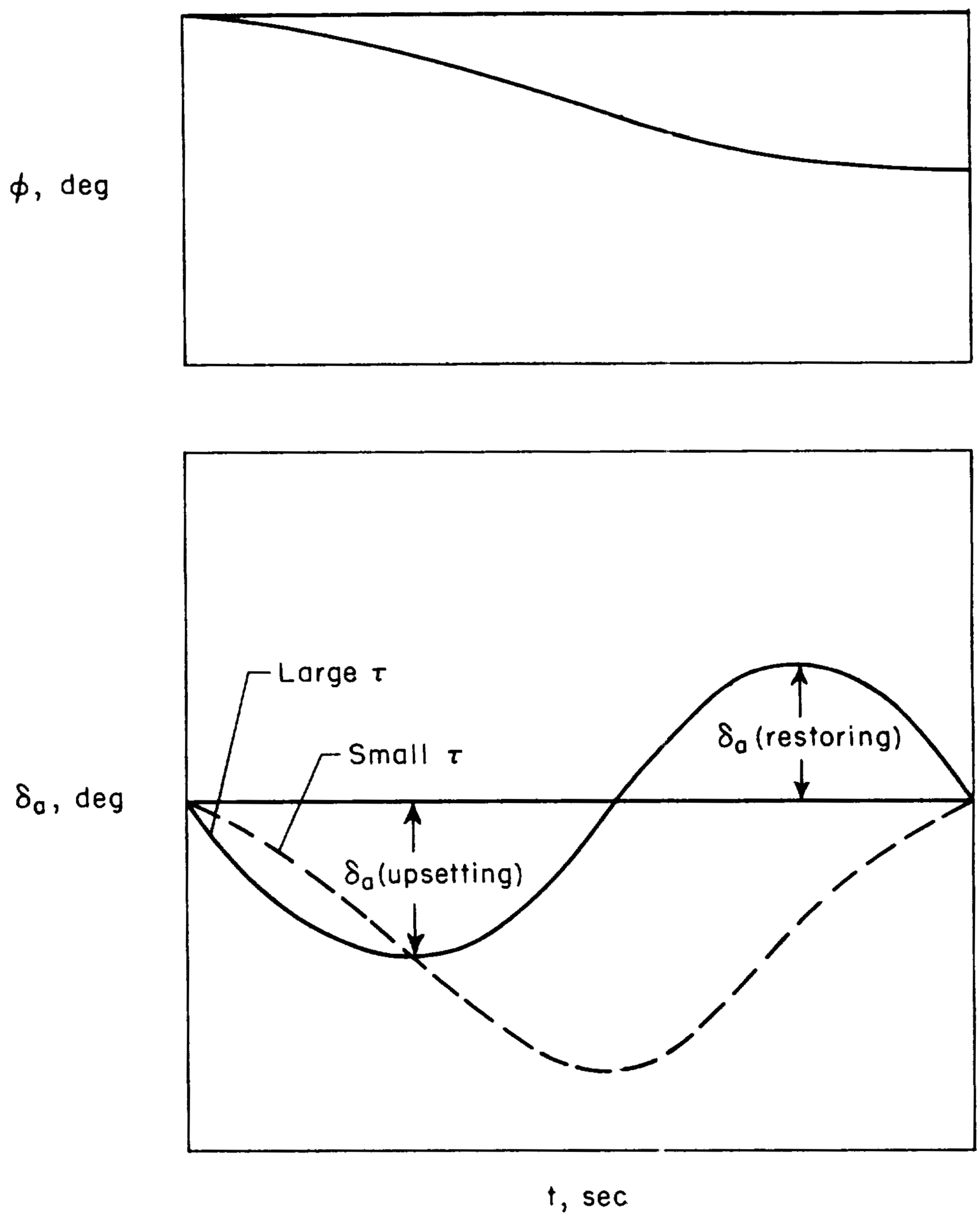


Figure 12.- Theoretical aileron movements required for a given bank angle change for airplanes with small and large time constants.

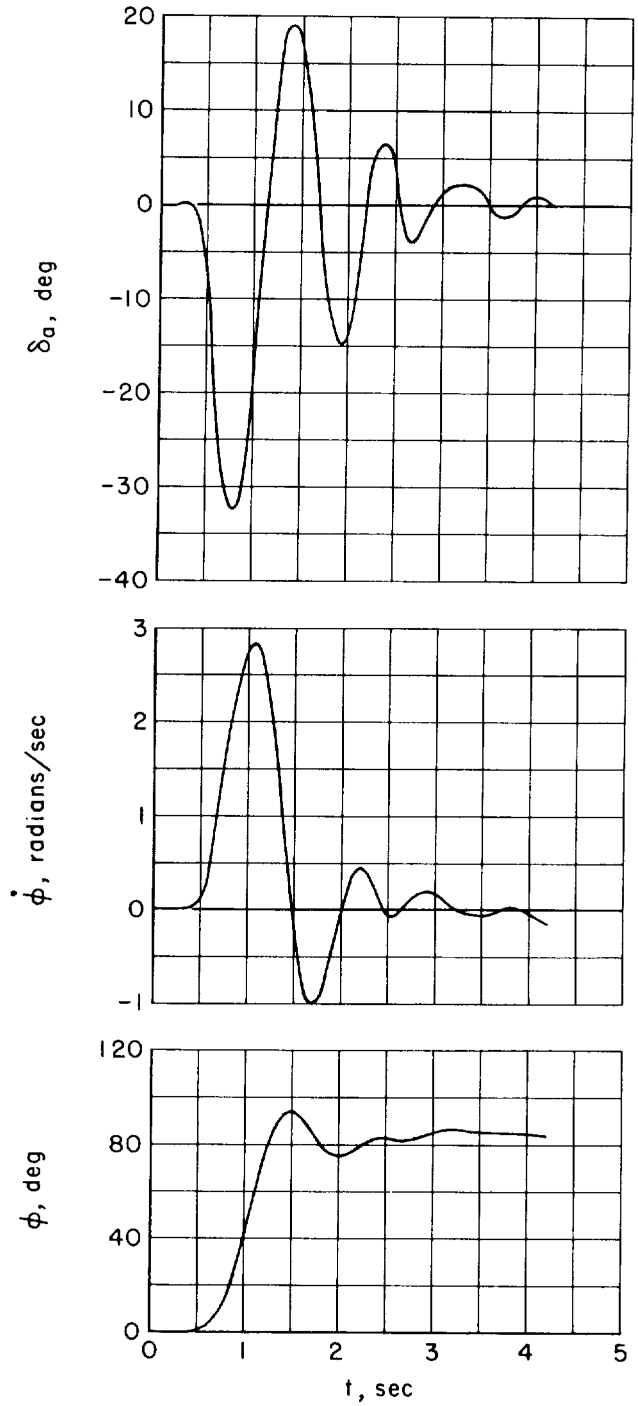


Figure 13.- Flight time history of a pilot's attempt to roll rapidly to a given bank angle with an airplane having a large τ and large $L_{\delta_a}\delta_{a,max}$ value.

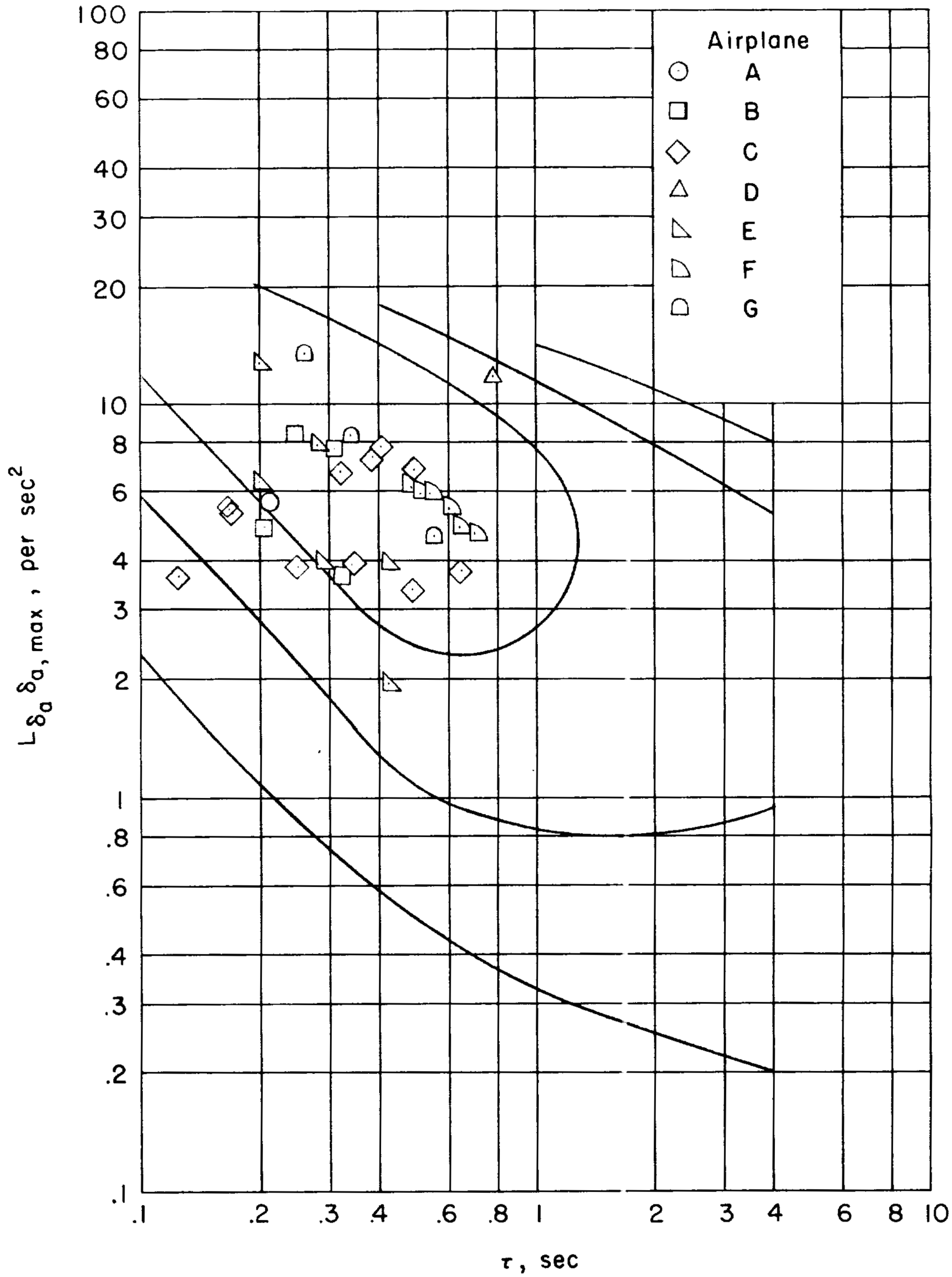


Figure 14.- Range of parameters, $L_{\delta_a}\delta_{a,max}$, anl τ, covered in the flight investigation, shown in comparison with the motion simulator derived boundaries.

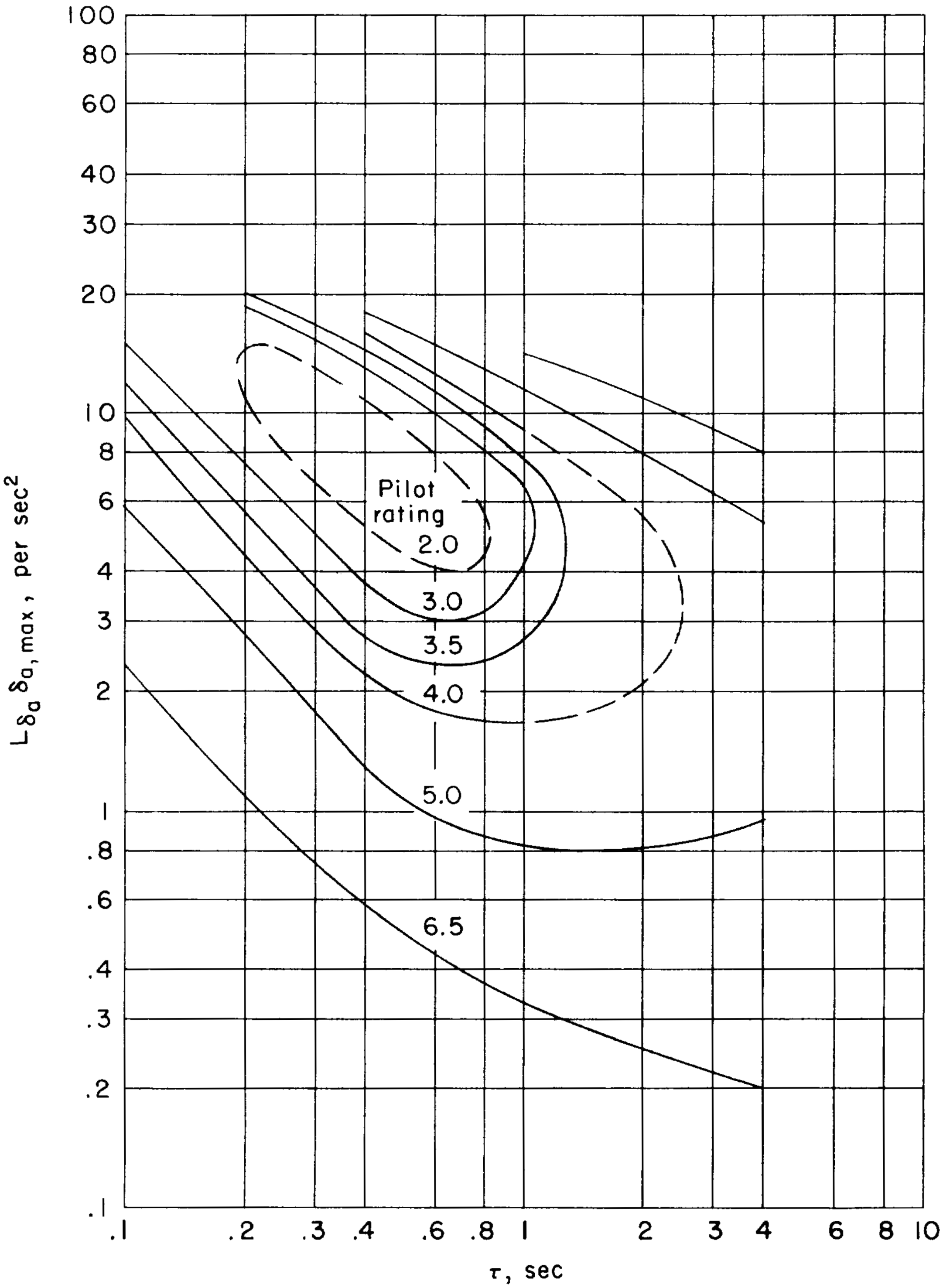


Figure 15.- Roll simulator derived pilot opinion contours for predicting pilot opinion of fighter roll performance.

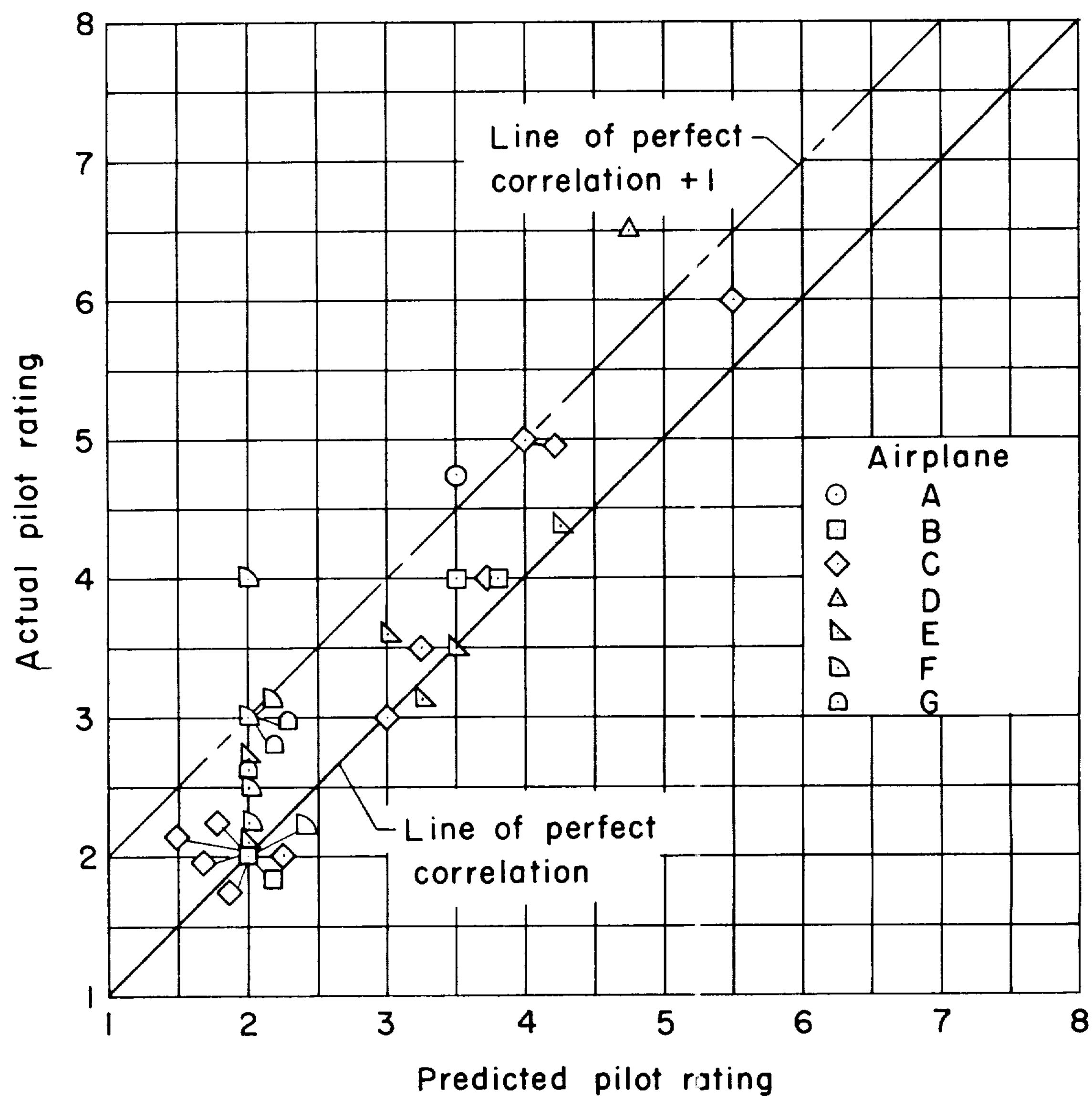


Figure 16.- Comparison of in-flight pilot-opinion rating with those predicted from flight simulator boundaries.

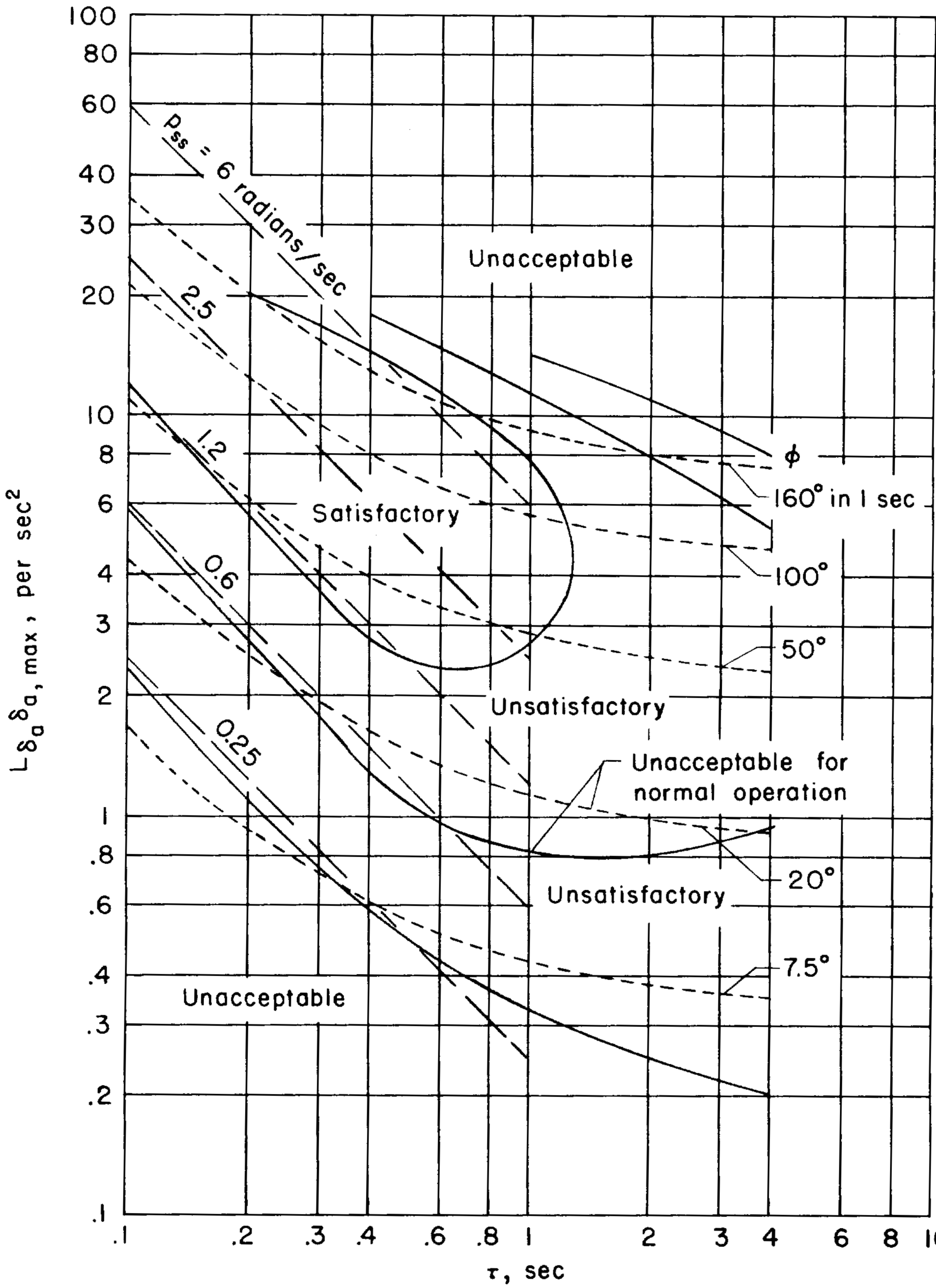


Figure 17.- Comparison of the derived roll performance criterion with the roll performance concept based on bank angle displacement at end of 1 second.

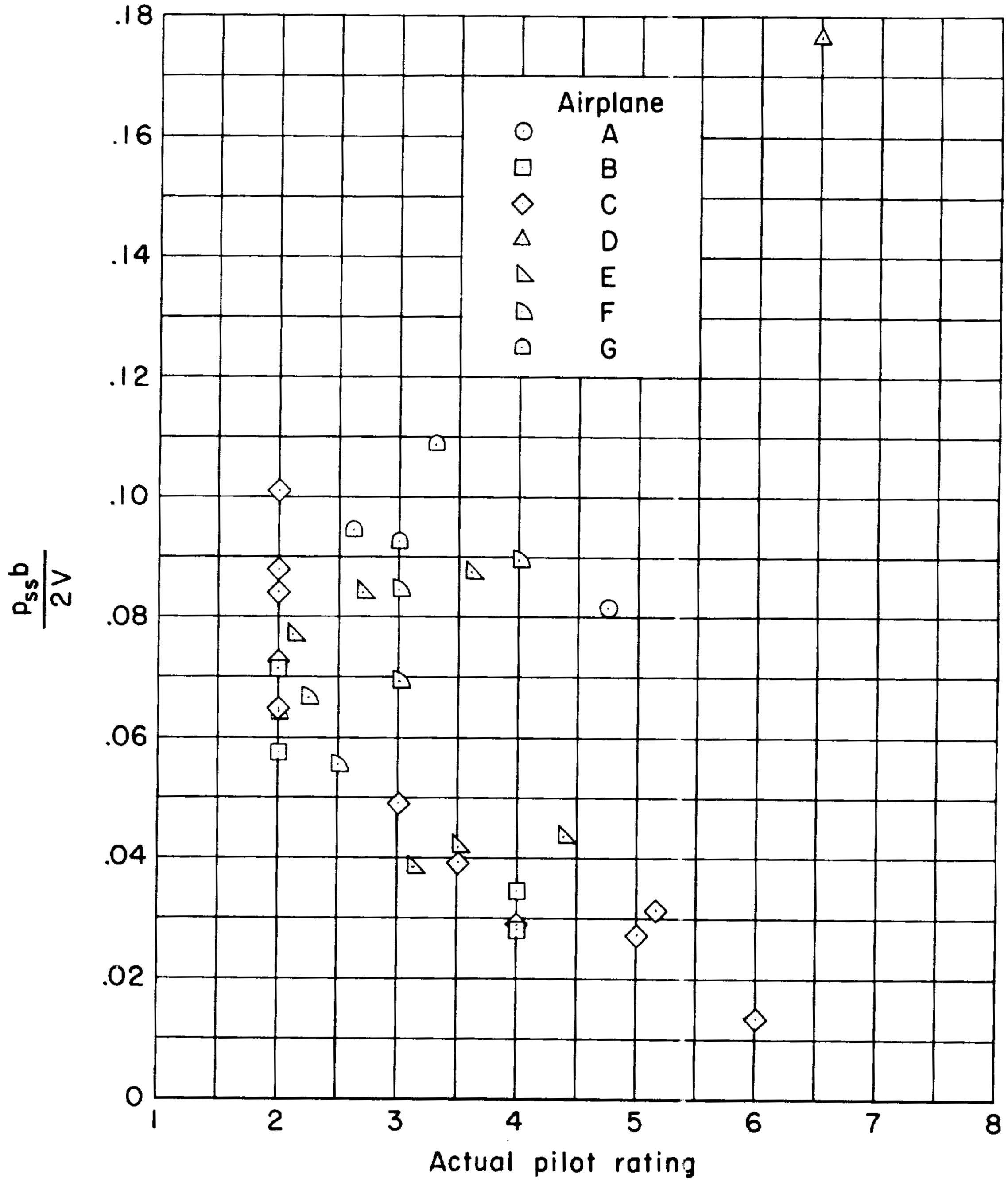


Figure 18.- Comparison of flight test pilot opinion with the parameter $\frac{p_{ss}b}{2V}$.